



# HERBACEOUS FEEDSTOCK 2020 STATE OF TECHNOLOGY REPORT

September 2020

*Changing the World's Energy Future*

Yingqian Lin, Mohammad Sadekuzzaman Roni, David N Thompson, Damon S Hartley, Mike Griffel, Hao Cai



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## EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) promotes the production of advanced liquid transportation fuels from lignocellulosic biomass by funding fundamental and applied research that advances the State of Technology (SOT). As part of its involvement with this mission, Idaho National Laboratory (INL) completes an annual SOT report for biomass feedstock logistics. This report summarizes supply system impacts of Bioenergy Technologies Office (BETO)-funded research and development efforts at INL and elsewhere (such as the High-Tonnage Feedstock Logistics projects (Webb et al. 2013a, Webb et al. 2013b, Webb et al. 2013c, Webb and Sokhansanj 2014, Sokhansanj et al. 2014)) that lead to improvements in feedstock supply systems. These include improvements to and observed performance of innovative harvest and collection methods, storage technologies, transportation and handling approaches, and advanced preprocessing technologies. Biomass quality and variability, and the interface between feedstock quality and conversion performance are key drivers in addition to delivered feedstock cost. In this report, we estimate the benefits of R&D technology improvements to individual supply system unit operations and present the status of feedstock logistics technology development for converting herbaceous biomass into biofuels. These analyses are supported by experimental data where possible and help to align the SOT relative to the cost goals defined in the Multi-Year Plan.

The 2020 Herbaceous SOT incorporates an actively managed storage system for early-harvested bales which are typically > 30% moisture. The storage system utilizes a combination

of best management practices and “farm-scale technologies” such as enhanced in-storage drying to achieve storage stability objectives. A wrapped-bale mechanical ventilation concept for these very wet bales utilizes a combination of microbial self-heating and advective air flow (supplied by a commercial grain dryer blower) to reduce stack moisture from 30% to <20% in 30 days. This technical improvement positively affects storage dry matter loss and feedstock preprocessing performance within the feedstock logistics system.

Previous SOT results have confounded biomass supply assumptions from BT-16 that predicted an increasing supply year on year. To get a clearer presentation of cost impacts of technology improvements, in the 2020 SOT we utilized the same supply curves from BT-16 that were used for the 2019 SOT. The 2020 Herbaceous SOT report documents the current modeled cost of an herbaceous feedstock supply system from harvest to the pretreatment reactor throat for hydrocarbon fuel production via biochemical conversion, based on equipment and processes now available or potentially available in the near term. The modeled cost also considers both the required quality and the availability of the biomass resources. The 2020 Herbaceous SOT predicts a modeled delivered feedstock cost of \$80.10/dry ton (2016\$); this is a \$1.27/dry ton (2016\$) decrease from the 2019 Herbaceous SOT. Technology improvements that contributed to this modeled cost reduction include reduced cost in the feedstock preprocessing caused by reduced moisture from the newly designed field side storage. A greenhouse gas emissions (GHG) assessment was completed by Argonne National Laboratory using the 2020 Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET), estimating a decrease of 6.68 kg CO<sub>2</sub>e/ton from the 2019 SOT (84.16 kg CO<sub>2</sub>e/ton in the 2019 SOT to 77.48 kg CO<sub>2</sub>e/ton in the 2020 Herbaceous Feedstock SOT). This net reduction is attributed to reduced energy consumption in the hammer mill, reduced high emission feedstock used in the blend (less three-pass corn stover), and incorporation of the updated GREET model.

Moving forward in future years, we will implement use of the n<sup>th</sup>-supply scenario developed in FY19 and FY20 as a constant supply to focus on improvements due to BETO-funded technology improvements. Hence, in this report we also present the 2020 Herbaceous SOT recast using the supply curves and optimal depot and biorefinery locations determined for the n<sup>th</sup>-supply scenario (see Appendix B); this is presented in this report as the 2020 Herbaceous n<sup>th</sup>-Supply SOT. Overall, by incorporating the biomass availability and depot locations optimized or the demand-based supply from the POLYSYS demand runs, the delivered feedstock cost decreased by \$1.31/dry ton from the 2020 Herbaceous SOT. Noting that this brings the delivered cost below the 2022 Herbaceous Projection, which was based on projected 2022 supply curves from BT-16, it will be necessary to recast the 2022 Herbaceous Projection to the n<sup>th</sup>-supply scenario during FY21 to put them on the same supply basis for comparison. It will also be necessary in the future to recast the 2030 Herbaceous Projection of \$71.26/dry ton (2016\$) to bring the SOTs and targets to the same supply basis.

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## 1. BACKGROUND

The Energy Independence and Security Act (EISA) of 2007 required a minimum supply of 36 million gallons of renewable fuels per year by 2022. In order to achieve these goals, the Bioenergy Technologies Office (BETO) has set cost and technology targets for producing advanced and cellulosic biofuels. One of the targets is to validate feedstock supply infrastructures and systems with 90% overall operating effectiveness (Hartley et al. 2020) and field-to-reactor throat delivered cost less than \$85.51/dry ton (2016\$). As stated by the 2017 Multi-Year Program Plan (DOE 2017), the research and development focus of the Feedstock Technologies (FT) platform is reducing the cost, improving the supply chain logistic efficiency, improving biomass quality, and increasing the supply volume. In addition, BETO oversees annual State of Technology (SOT) report that assesses current technologies that are relevant to BETO's targets based on actual data and experimental results.

Feedstocks are essential to achieving BETO goals because the cost, quality, and quantity of feedstock available and accessible at any given time limit the maximum volume of biofuels that can be produced. In accordance with the 2016 Multi-Year Program Plan (DOE 2016a), FT focuses on (1) reducing the delivered cost of sustainably produced biomass, (2) preserving and improving the physical and chemical quality parameters of harvested biomass to meet the individual needs of biorefineries and other biomass users, and (3) expanding the quantity of feedstock materials accessible to the bioenergy industry. This is done by identifying, developing, demonstrating, and validating efficient and economical integrated systems for harvest and collection, storage, handling, transport, and preprocessing raw biomass from a variety of crops to reliably deliver the required supplies of high-quality, affordable feedstocks to biorefineries as the industry expands. The elements of cost, quality, and quantity are key considerations when developing advanced feedstock supply concepts and systems (DOE 2016a).

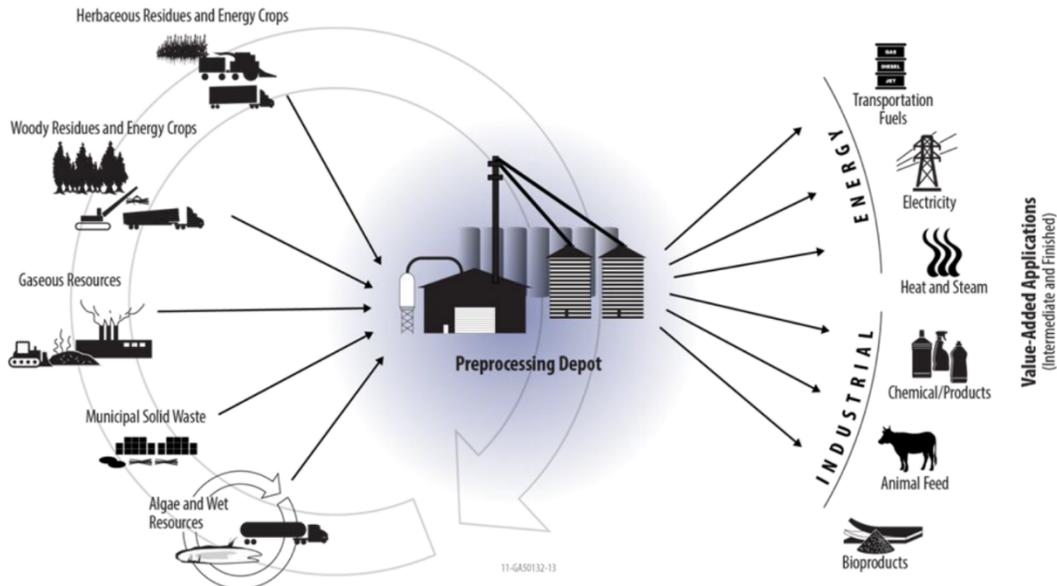
### Progression of Feedstock Supply System Designs

Feedstock supply systems are highly complex systems of operations required to move and transform biomass from a raw harvested material at the point of production into a formatted, on-spec feedstock at the throat of the conversion reactor. Feedstock logistics can be broken down into individual operations of harvest and collection, storage, transportation, preprocessing, and queuing and handling. Designing economic and environmentally sustainable feedstock supply systems, while providing necessary resource quantities at the appropriate quality, is critical for growth of the bioenergy industry. Research and development on feedstock supply systems aims to reduce delivered cost, improve and preserve feedstock quality, and expand access to biomass resources. Through 2012, BETO-funded research on feedstock supply systems focused on improving conventional feedstock supply systems (CFSS). CFSS designs rely on existing technology and systems to supply feedstock to biorefineries (Hess et al. 2009a). These designs tend to be vertically integrated with a specific conversion process or biorefinery. They also create the requirement to design extremely robust conversion systems capable of handling variability in feedstock quality at the biorefinery. Biorefineries strive to optimize efficiencies and capacities within the constraints of local supply, equipment availability, and permitting requirements. However, this approach makes the system vulnerable to variations in feedstock

quality parameters, such as (a) high ash content, which negatively impacts operating costs related to acid consumption and ash disposal; (b) variable composition of convertible carbohydrates, which negatively impacts sugar yields due to suboptimal enzyme loading; and (c) variable moisture, which increases grinding costs and creates handling and flowability problems that significantly reduce the effectiveness of feedstock introduction to the conversion process.

CFSS designs are currently the backbone of the emerging biofuels industry. However, conventional supply systems have limitations that restrict widespread implementation on a national scale (Hess et al. 2009a, Hess et al. 2009b). Viability of the conventional supply system's design is reliant on geographical areas that have a concentrated supply of abundant, easily accessible, and low-cost biomass resources (such as corn stover in the Midwestern United States). Within these regions, variable weather, inherent compositional variability and harvest practices that are not designed to mitigate quality concerns, such as moisture and ash content, leads to considerable variability in feedstock cost and the biorefinery's ability to process the biomass. Low density bales in conventional systems combined with the short window of availability necessitate large-scale bale storage, leading to greatly increased fire risk. Moving outside these select regions, the feedstock supply system must be further adapted to accommodate a diversity of feedstocks to ensure adequate supply, which leads to changing cost, quality, and conversion yields that are directly tied to the conversion facility's size constraints. CFSS can only address feedstock quality indirectly through passive controls, such as resource selection or best management practices. For example, research at INL has shown that varying harvesting practices and equipment can reduce ash (i.e., dirt) entrainment during harvest and baling (Bonner et al. 2014). When positioned in a highly productive single resource area, biorefineries can be selective in contracting only biomass that meets their specifications. However, biomass quality (e.g., ash and moisture content) is highly variable both spatially and temporally (Kenney et al. 2013), and, in any given year, passive controls might not provide sufficient quality control for the feedstock to meet desired specifications. Therefore, biorefineries that rely on conventional designs are constrained to local resources, with cost-prohibitive expansion of the collection radius limiting plant size (Graham et al. 2013). Several analyses have shown that as the biofuels industry expands past the highly productive regions, CFSS will fail to meet supply requirements (Hess et al. 2009b, Bonner et al. 2014) economically or at the desired price target.

To meet the demands of the future bioenergy industry, the supply system must expand beyond CFSS in certain areas to what has been termed "advanced" feedstock supply systems (Hess et al. 2009a, Hess et al. 2009b, Searcy et al. 2010, Jacobson et al. 2014). For advanced feedstock supply system (AFSS) designs, a distributed network of aggregation and processing centers, termed "depots," are employed near the point of biomass production (i.e., the field or forest) to reduce biomass variability and produce feedstocks of a uniform format, necessary to move toward biomass commoditization (Figure 1). The depots produce a stable, tradable, merchandisable intermediate that reduce downstream conversion inefficiencies and move the burden of feedstock variability away from the biorefinery.



**Figure 1.** Incorporation of stakeholder feedback has resulted in improvements in advanced feedstock supply systems, evolving depots from being vertically integrated to producing merchandisable intermediates and serving a variety of customers and markets.

Advanced concepts have evolved (and continue to evolve) as new research and ideas emerge. Advanced concepts are also guided by input from stakeholders. In February 2015, the Advanced Feedstock Supply System Validation Workshop gathered experts from industry, DOE offices, DOE-funded laboratories, and academia to discuss approaches for addressing challenges associated with an expanding bioenergy industry and assumptions used in the Advanced Feedstock Supply System. The workshop was sponsored by DOE-BETO and feedback received is being considered as advanced concepts evolve (Searcy et al. 2015).

Depots can provide logistics solutions for sourcing multiple biomass resources to a biorefinery, whether these resources are dispersed or co-located. In such a scenario, depots may emerge as feedstock supply chain business elements to lessen the complexity to a biorefinery of managing a blended feedstock supply system. An economic advantage of a depot in this scenario may be its specialization to supply and preprocess single sources of improved quality, value-added biomass (referred to as a “blendstock”) that can be formulated together with blendstocks from other depots to produce cost-effective feedstocks meeting the specifications of numerous customers. This specialization eliminates the need for a single entity to make a capital investment and establish expertise to contract, preprocess, and supply a diversity of resources that may have different preprocessing requirements. Relying on multiple biomass types and sources to produce blended feedstocks can also reduce the risk to industry by diversifying reliance on any one feedstock.

The 2020 Herbaceous SOT applies blending of multiple types of herbaceous biomass as a means of increasing access to biomass resources and meeting feedstock quality and cost specifications, which is a critical step toward feedstock commoditization. Blending refers to combining different types of biomass to consistently provide a uniform feedstock of known specifications for a conversion process at the lowest possible cost. An optimization model (Roni et al. 2019b) is used to determine least cost blend. The 2020 Herbaceous SOT incorporates two depots that are located at a distance from the biorefinery in higher-yielding counties that have significant corn stover available lower on the supply curve.

The 2020 Herbaceous SOT requires 725,000 dry tons feedstock to be delivered to the reactor throat annually. In past SOTs we have estimated farm-gate biomass availability based on yearly supply projections presented in the 2016 Billion-Ton Report (BT16) (DOE 2016b), which led to confounding of delivered cost reductions due to supply availability assumptions with cost reductions arising from BETO R&D investment. To eliminate this problem for the 2020 Herbaceous SOT, we utilized the same supply curves used in the 2019 Herbaceous SOT (Roni et al. 2019a). This allowed a singular focus on delivered cost improvements arising from technology advancements. Moving forward in future years, we will implement use of the  $n^{\text{th}}$ -supply scenario developed in FY19 and FY20, in conjunction with Oak Ridge National Laboratory, as a constant supply in order to focus on improvements due to BETO-funded technology improvements. Hence, in this report we also present the 2020 Herbaceous SOT recast using the supply curves and optimal depot and biorefinery locations determined for the  $n^{\text{th}}$ -supply scenario (see Appendix B); this is presented in this report as the 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT following presentation of the 2020 Herbaceous SOT.

## 2. 2020 Herbaceous Feedstock SOT

The Biomass Logistics Model (BLM) was used to model feedstock logistics cost and energy consumption estimates for the 2020 Herbaceous Feedstock SOT design. The BLM incorporates information from a collection of databases that provide (1) engineering performance data for hundreds of equipment systems, (2) spatially explicit labor cost data sets, and (3) local tax and regulation data. The BLM's analytic engine is built in the system dynamics software package Powersim™. The BLM is designed to work with thermochemical- and biochemical-based biofuel conversion platforms and to accommodate a range of lignocellulosic biomass types (e.g., herbaceous residues, short-rotation woody and herbaceous energy crops, woody residues, and algae). The BLM simulates the flow of biomass through the entire supply chain while tracking changes in feedstock characteristics (i.e., moisture content, dry matter, ash content, and dry bulk density) and calculating cost and energy consumption (Cafferty et al. 2013b). The energy consumption and other parameters (e.g. transportation distance, density) from BLM are also inputs to the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET 2016), to perform a cursory farm gate-to-plant gate life-cycle assessment on GHG emissions (this is completed by colleagues at Argonne National Laboratory for this report).

### 2.1 Description of Logistics System Design

The 2020 Herbaceous SOT design assumes annual n<sup>th</sup>-plant delivery of 725,000 dry tons of herbaceous feedstock, with biochemical conversion in-feed feedstock compositional specifications presented in Table 1 (Davis et al. 2013). The shaded rows in Table 1 show the compositional specifications for the feedstock, namely, 59% carbohydrates, ≤ 5 % ash, and 20% moisture. An additional specification is ¼”-minus particle size at the pretreatment reactor throat.

**Table 1.** *Delivered feedstock composition assumptions for dilute-acid pretreatment and enzymatic hydrolysis to sugars followed by biological conversion of sugars to hydrocarbons pathway (Humbird et al. 2011, Davis et al. 2013).*

<b>Component</b>	<b>Composition (dry wt. %)</b>
<b>Glucan</b>	35.05
<b>Xylan</b>	19.53
<b>Lignin</b>	15.76
<b>Ash</b>	4.93
<b>Acetate</b>	1.81
<b>Protein</b>	3.10
<b>Extractives</b>	14.65
<b>Arabinan</b>	2.38
<b>Galactan</b>	1.43
<b>Mannan</b>	0.60
<b>Sucrose</b>	0.77
<b>Total structural carbohydrate</b>	<b>58.99</b>
<b>Total structural carbohydrate + sucrose</b>	<b>59.76</b>
<b>Moisture (bulk wt.%)</b>	<b>20.0</b>

The 2020 Herbaceous SOT is reported in 2016\$ and includes grower payment, logistics costs, and ash and moisture dockages to reflect a modeled net delivered feedstock supply cost. The modeled logistics system for the 2020 Herbaceous SOT delivers 725,000 dry tons of a 29.63% three-pass corn stover – 70.37% two-pass corn stover blend, utilizing the harvest, collection and transportation system described in the 2019 Herbaceous SOT report (Roni et al., 2019a) and summarized in Appendix A. The 2020 Herbaceous SOT also incorporates an actively managed storage system comprised of a combination of best management practices and “farm-scale technologies” such as enhanced in-storage drying to achieve storage stability objectives for early-harvested wet bales and predicts a modeled delivered feedstock cost of \$80.10/dry ton (2016\$); this is a \$1.27/dry ton decrease from the 2019 Herbaceous SOT.

### 2.1.1 Resource Availability

The geographic area for the 2020 Herbaceous SOT is northwestern Kansas, with the biorefinery located in Sheridan County, which is unchanged from the 2019 Herbaceous SOT. It

was assumed that all corn stover and switchgrass biomass located in Kansas, Nebraska and Colorado that could be sustainably harvested would be potentially available to meet the demand of 725,000 dry tons delivered to the pretreatment reactor throat at the biorefinery. In the 2020 Herbaceous SOT, biomass availability is assumed to be same as in the 2019 Herbaceous SOT (Roni et al. 2019a) in order to track the economic impact of technical advancements from feedstock R&D. Biomass availability in the 2019 Herbaceous SOT was estimated by utilizing the projected 2019 supply curves from the BT16 report, modified to incorporate new (FY19) models of the impact of implementing the ILM strategy in the supply shed (completed by WBS 4.2.1.20) and of the predicted grower participation rates with the implementation of ILM (completed by WBS 1.2.1.5).

### 2.1.2 Harvest and Collection

Corn stover is the primary feedstock in the 2020 Herbaceous SOT design; while switchgrass was considered as in the 2019 Herbaceous SOT design, it was not part of the least cost design and so is not included in this report. It is assumed that corn stover is harvested by both three-pass (conventional) and two-pass methods (advanced). The three-pass corn stover harvest and collection method refers to the conventional stover harvest strategy and is also referred to as a “multi-pass harvesting system.” The two-pass corn stover harvesting and collection method is an advanced, and more sustainable harvesting method, that eliminates the windrowing step (Birrell et al., 2014). Harvesting yields of three-pass corn stover and two-pass corn stover remain unchanged from the 2019 Herbaceous SOT (Roni et al., 2018), and are referenced from studies conducted by Smith and Bonner (2014).

### 2.1.3 Storage

The 2020 Herbaceous SOT incorporates an actively managed storage system comprised of a combination of best management practices and “farm-scale technologies” such as enhanced in-storage drying of high-moisture early harvested bales to achieve storage stability objectives. A newly constructed whole-bale dryer/permeameter is introduced to the storage process to dry the biomass with initial moisture content of >30% over 30 days storage time (Figure 2). By adding the dryer, microbially-generated heat is lost at higher rates which has a negative feedback on microbial respiration rate and heat generation. The bale dryer has been shown to reduce the moisture content from 30% to <20% and keep biodegradation and dry matter losses at <6%. Following field storage, the resulting average moisture content is assumed to be 20% (5% moisture loss). Both literature (Shah et al., 2011) and INL laboratory-scale storage experiments indicate that higher initial moisture content leads to greater dry matter loss; losses of individual compositional components of the biomass were estimated based on the results of INL laboratory storage experiments performed in WBS 1.2.1.1 (see Appendix A). Since the actively managed storage system will be limited to high moisture biomass, in the 2020 Herbaceous SOT design it

*Figure 2. Bale dryer/bale permeameter fabricated and used by INL to measure drying, internal temperatures, and moisture loss in whole bales. Air flow is from the right to the left in the photograph. The instrumentation on the right records the temperature and relative humidity of the air entering and exiting the bale, the internal bale temperatures, and the pressure drop across the bale. The instruments on the left periodically sample the inlet and outlet gases and measure CO<sub>2</sub>, water vapor, and gas tracer (SF<sub>6</sub>), which is metered in from the silver bag at*



is assumed that 50% of the harvested biomass has an initial moisture content of 25%, 25% of the harvested biomass has an initial moisture content of 20%, and the remaining 25% of the biomass has an initial moisture content of 30% (these would be the early harvested bales). With these assumptions, an average field-side stack dry matter loss of 8.88%/year was estimated for the overall corn stover storage.

### **2.1.4 Preprocessing**

Feedstock preprocessing in the 2020 Herbaceous SOT design remains the same as the 2019 Herbaceous SOT design, which included size reduction, grinding and densification. However, preprocessing operating conditions and performance were updated based on the altered biomass properties exiting from the new storage design. For example, since the biomass coming from storage will have lower moisture than in the 2019 Herbaceous SOT, the hammer mill will consume less energy. An EZ Ration Processor is used for the first stage size reduction, which is a horizontal bale processor originally designed for blending cattle feed components such as hay and corn stalks. The 3-rotating-drum debaling head design of the bale processor (Figure 3) requires lower rpm and energy and eliminates the slugging flow observed in the first stage hammer mill used in SOTs prior to 2019. Moreover, the EZ Ration bale processor can feed the two bales at separate feed rates (this feature was originally developed by the manufacturer for the cattle feed blending function). This could be an advantage for blending bales with different moisture contents to mitigate very wet bales, or for blending bales of different biomass types. Pilot-scale testing was performed during FY20 in the Biomass Feedstock User Facility (BFNUF) at INL (WBS 1.2.3.3) to collect the parametric data for preprocessing.



*Figure 3. EZ Ration Debaling System.*

### **2.1.5 Transportation and Handling**

Transportation and handling include all steps involved in the movement of biomass from multiple local locations to a centralized location (such as a preprocessing facility or biomass depot), including loading, trucking, and unloading. Feedstock transportation in the 2020 Herbaceous SOT includes both bale and pellet transportation, which are described in the 2019 Herbaceous SOT (Roni et al., 2019a) and shown in Appendix A. In bale transportation, biomass bales are loaded onto semi-trucks after the field side storage, transported, and unloaded at the depots. After pelleting, biomass pellets are then loaded and transported to the biorefinery.

### **2.1.6 Cost Summary and Energy Usage**

Results of the supply chain analysis are summarized in Table 2, which provides the detailed cost breakdown and greenhouse gas emissions. The greenhouse gas emissions analysis was completed by Argonne National Laboratory (ANL), using energy consumption and transportation distance data from the BLM. ANL employed the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET<sup>®</sup>) (Argonne National Laboratory, 2017) to conduct detailed life-cycle analysis of farm gate-to-biorefinery gate GHG emissions of the herbaceous biomass scenarios presented in this report.

**Table 1.** The 2020 Herbaceous SOT modeled cost and GHG estimates for an herbaceous feedstock supply system supplying 725,000 dry tons annually in northwestern Kansas. Design details are provided in Appendix A.

Cost Element	Cost (\$/dry ton)			GHG emissions (kg CO <sub>2</sub> e/ton)
	Three-Pass Stover	Two-Pass Stover	Least-Cost Blend <sup>b</sup>	
<b>Blend Ratio</b>	29.63%	70.37%	100.00%	
<b>Grower payment</b>	\$21.71	\$20.16	\$20.62	
<b>Harvest and collection</b>	\$13.84	\$18.79	\$17.33	11.17
<b>Storage and queuing</b>	\$6.66	\$6.74	\$6.72	2.50
<b>Transportation and handling</b>	\$13.74	\$14.97	\$14.61	16.60
<b>In-plant receiving and preprocessing</b>	\$19.43	\$19.43	\$19.43	47.21
<b>Dockage</b>	\$2.59	\$0.89	\$1.39	
<b>Total</b>	<b>\$77.97</b>	<b>\$80.98</b>	<b>\$80.10</b>	<b>77.48</b>

a Pesticide and fertilizer emissions incurred during biomass production were attributed to the biomass growth stage of the life cycle and are not included.

b The blend costs are presented as the weighted average of the blend component costs.

c Grower payment taken as the cost assumed for procurement of grass clippings.

Table 3 shows the modeled cost estimates for the herbaceous feedstock supply system for the 2019 SOT, 2020 SOT and the 2022 Projection. The small increase of \$0.06/dry ton in grower payment from the 2019 Herbaceous SOT is a result of increasing the proportion of two-pass corn

**Table 3.** Summary of modeled cost estimates for the herbaceous feedstock supply system for biochemical conversion pathway for the 2019 SOT, 2020 SOT and 2022 Projection.

	2019 SOT	2020 SOT	2022 Projection
<b>Feedstock Blend</b>	<b>Blend</b>	<b>Blend</b>	<b>Blend</b>
<b>Net delivered cost (\$/dry ton)</b>	<b>\$81.37</b>	<b>\$80.10</b>	<b>\$79.07</b>
Grower payment (\$/dry ton)	\$20.56	\$20.62	\$22.37
<b>Feedstock logistics (\$/dry ton)</b>	<b>\$60.81</b>	<b>\$59.47</b>	<b>\$56.70</b>
Harvest & collection (\$/dry ton)	\$17.14	\$17.33	\$12.79
Storage & queuing (\$/dry ton)	\$6.49	\$6.72	\$8.35
Preprocessing (\$/dry ton)	\$20.84	\$19.43	\$21.44
Transportation & handling (\$/dry ton)	\$14.76	\$14.61	\$12.44
Dockage (\$/dry ton)	\$1.58	\$1.39	\$1.68

stover in the blend. The \$0.19/dry ton increase in harvest and collection costs from 2019 results from the higher harvesting cost of two-pass corn stover, which is the largest component of the blend and is required to meet the carbohydrate specification.

In the 2020 Herbaceous SOT, a commercial grain dryer blower was included the field storage for early harvested bales, which allowed the overall average stack moisture content to decrease from 25% to 20%, and reduce dry matter loss from 12% to a weighted estimate of 8.88% compared to the 2019 Herbaceous SOT. Hence, there was \$0.23/dry ton increase in feedstock in storage cost in the 2019 SOT. The \$1.41/dry ton reduction in preprocessing is a composite result of increased performance in the hammer mill due to the lower moisture coming from storage. Due to the lower moisture exiting storage and to the reduction in total transported biomass (due to reduced dry matter loss), the total transportation cost was reduced by \$0.15/dry ton. The decrease of \$0.19/dry ton in dockage is attributed to the increased amount of lower ash two-pass corn stover in the blend (note that dockage is included in the optimization as a cost component). A greenhouse gas emissions (GHG) assessment was completed by Argonne National Laboratory using the 2020 Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET), estimating a decrease of up to 6.68 kg CO<sub>2</sub>e/ton from the 2019 SOT (84.16 kg CO<sub>2</sub>e/ton in the 2019 SOT to 77.48 kg CO<sub>2</sub>e/ton in the 2020 Herbaceous Feedstock SOT). This net reduction is attributed to reduced energy consumption in the hammer mill, reduced high emission feedstock used in the blend (less three-pass corn stover), and incorporation of the updated GREET model.

As stated above, the least-cost blend for this analysis consisted of 29.63% three-pass corn stover and 70.37% two-pass corn stover. The amounts of harvested biomass (prior to storage) required to produce this blend are shown in Table 4, along with their carbohydrate and ash compositions and individual delivered costs. The depot locations, biomass source counties and biorefinery location are listed in Table 5 and Table 6 and are shown pictorially in Figure 4. The least cost supply chain network utilized two distributed depots (Nodes 23 and 25 in Figure 4) for a biorefinery located in Sheridan County, Kansas. To avoid exceeding the capacity of depot at Node 25, a small portion of the two-pass corn stover purchased from Node 18 is distributed to the depot at Node 23. The results also show that a biorefinery with a design capacity of 725,000 dry tons/year, would need to procure at least 811,180 dry tons of biomass annually to account for losses in the system. This procured biomass is 29,487 dry tons less than the 2019 Herbaceous SOT.

**Table 4.** Delivered (reactor-throat) costs and compositions of the herbaceous biomass sources, the preprocessed blendstocks produced from these biomass sources, and the least-cost blend. The modeled cost estimates are for delivery of 725,000 dry tons/year of blended feedstock at 59.00% carbohydrate, 8.63% ash and 11.41% moisture, and are discussed in detail in Appendix A. An ash dockage of \$1.37/dry ton and a moisture dockage of \$0.03/dry ton are included in the total delivered blend cost. All costs are in 2016\$.

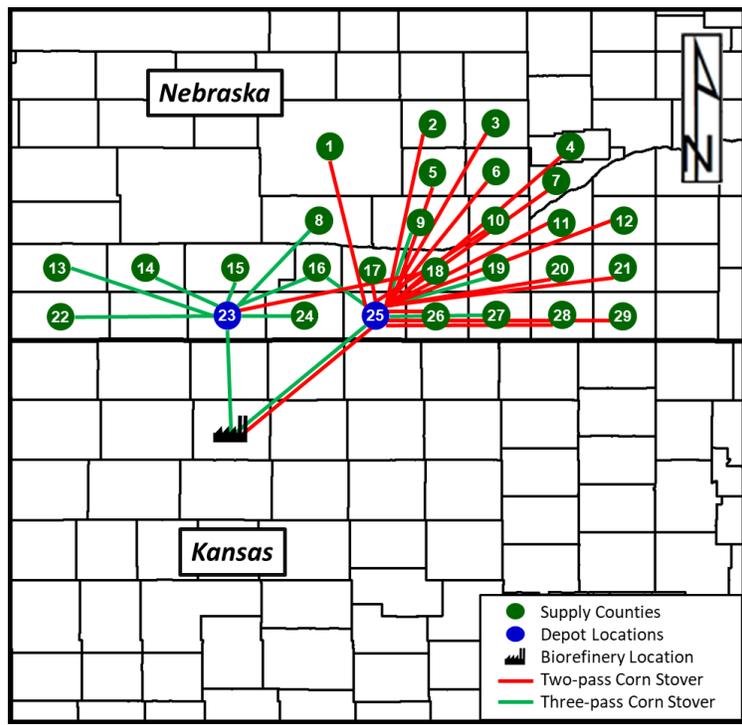
Biomass Type	Raw Biomass Purchased (dry tons)	Pelleted Blendstocks		Delivered Cost (\$/dry ton)
		Produced (dry tons)	Total Carbohydrates (wt% db)	
Three-pass corn stover	240,350	214,815	57.10%	\$77.97
Two-pass corn stover	570,830	510,185	59.80%	\$80.98
<b>Totals</b>	<b>811,180</b>	<b>725,000</b>	<b>59.00%</b>	<b>\$80.10</b>

**Table 5.** Node IDs and county names for the biomass source counties for the supply system depicted in Figure 3. The depot counties (nodes 23 and 25) are also farm-gate biomass source counties.

Node	County	Node	County
-	Sheridan County, KS	15	Frontier County, NE
1	Custer County, NE	16	Gosper County, NE
2	Valley County, NE	17	Phelps County, NE
3	Greeley County, NE	18	Kearney County, NE
4	Nance County, NE	19	Adams County, NE
5	Sherman County, NE	20	Clay County, NE
6	Howard County, NE	21	Fillmore County, NE
7	Merrick County, NE	22	Dundy County, NE
8	Dawson County, NE	23	Red Willow County, NE
9	Buffalo County, NE	24	Furnas County, NE
10	Hall County, NE	25	Harlan County, NE
11	Hamilton County, NE	26	Franklin County, NE
12	York County, NE	27	Webster County, NE
13	Chase County, NE	28	Nuckolls County, NE
14	Hayes County, NE	29	Thayer County, NE

**Table 6.** Optimal locations and sizes of distributed depots for least cost delivery of 725,000 dry tons/year of blended feedstock to Sheridan County, KS. Nodes are identified by county name in Table 5 and are shown geographically in Figure 3.

Node	Identifier	County	Capacity (dry tons/yr)	Biomass Type	Biomass Source Nodes
-	Biorefinery	Sheridan, KS	725,000	Blend	23, 25
23	Depot	Red Willow, NE	162,169	three-pass corn stover	8, 13, 14, 15, 16, 22, 23, 24
				two-pass corn stover	18
				three-pass corn stover	9, 16, 19, 27
25	Depot	Harlan, NE	562,831	two-pass corn stover	1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 17, 20, 21, 25, 26, 28, 29



**Figure 4.** Supply chain network design for the 2020 Herbaceous SOT. The supply chain has 2 distributed depots (Nodes = 23 and 25) with the biorefinery located in Sheridan County, Kansas. Three-pass corn stover is sourced from Nodes 8, 9, 13, 14, 15, 16, 19, 22, 23, 24 and 27. Two-pass corn stover is sourced from Nodes 1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 17, 18, 20, 21, 25, 26, 28 and 29. County names are shown with their node identifiers in Table 5 and Table 6.

### 2.1.7 Sensitivity Analysis of Costs

Sensitivity analysis was performed on the delivered feedstock cost for the 2020 Herbaceous SOT. Critical process parameters were investigated to determine the impact of uncertainty in their values on the delivered feedstock cost. The parameters varied in the sensitivity analysis are shown in Table 7.

*Table 7. Model parameters varied for the sensitivity analysis. Each parameter was varied independently based on actual variations observed in experimental and field data.*

Parameter	Units	Biomass Type	Minimum	Average (SOT)	Maximum
Effective windrowing rate <sup>a</sup>	acres/hr	Three-pass corn stover	10.78	11.5	12.51
		Two-pass corn stover	n.a.	n.a.	n.a.
Effective baling rate <sup>b</sup>	dry ton/hr	Three-pass corn stover	16.14	26.18	28.10
		Two-pass corn stover	8.88	14.4	24.7
Field side storage dry matter loss <sup>c</sup>	%	Three-pass corn stover and Two-pass corn stover	5.58%	8.88%	14.21%
Bale transport loading/unloading time <sup>d</sup>	minutes	Three-pass corn stover and Two-pass corn stover	39	42	45
Bale density <sup>e</sup>	lb/ft <sup>3</sup>	Three-pass corn stover and Two-pass corn stover	11	12	13
Hammer mill effective throughput <sup>f</sup>	dry tons/hr/machine	Three-pass corn stover and Two-pass corn stover	2.61	2.92	3.24
Hammer mill effective energy consumption <sup>f</sup>	kWh/dry ton	Three-pass corn stover and Two-pass corn stover	28.0	35.0	42.0
Bale processor throughput <sup>f</sup>	dry tons/hr/machine	Three-pass corn stover and Two-pass corn stover	5	10	13
Bale processor energy consumption <sup>f</sup>	kWh/dry ton	Three-pass corn stover and Two-pass corn stover	6.5	8.0	11.0
Pelleting throughput <sup>f</sup>	dry tons/hr/machine	Three-pass corn stover and Two-pass corn stover	3.43	3.62	3.76
Pelleting energy consumption <sup>f</sup>	kWh/dry ton	Three-pass corn stover and Two-pass corn stover	33.79	32.49	34.68

**Table 7. (continued)**

Parameter	Units	Biomass Type	Minimum (SOT)	Average (SOT)	Maximum (SOT)
Bypass during fractional milling <sup>g</sup>	%	Three-pass corn stover and Two-pass corn stover	26.0	30.0	32.7
Interest rate <sup>h</sup>	%	Three-pass corn stover and Two-pass corn stover	4.0	8.0	12.0

a: Effective windrowing rate is varied based on variation of field efficiency measured from time series data (Roni et al., 2018).  
 b: Depends on variation of yield and equipment capacity. Empirical field data from DOE co-sponsored Biomass Alliance for Logistics Efficiency and Specifications (BALES) project (Comer, 2017) and DOE-sponsored “Growing Bioeconomy Markets: Farm-to-Fuel in Southside Virginia” project (DOE.,2017).were utilized to measure the variation in two-pass corn stover and switchgrass .The variation in three-pass corn stover was estimated by normalizing the two-pass corn stover data by applying actual baling rate during three-pass corn stover baling.  
 c: Assumed based on observed variation during storage  
 d: Bale load time variation is measured from variation of bale loads by Stinger ALSS (STINGER,2015).  
 e: Variation is measured based on empirical data from DOE funded integrated landscape design project (Roni et al., 2018).  
 f: INL PDU data and Forest Concepts data were utilized to measure the variation in throughput and energy consumption under base case process conditions (e.g. moisture, screen size) for corn stover and switchgrass. Switchgrass percentage variation of throughput and energy consumption from base case is utilized to estimate the grass clippings variations  
 g: INL PDU data were utilized to measure the variation in percentage of material by bypassed during second stage grinding under base case process conditions (e.g. moisture, screen size) for corn stover and switchgrass  
 h: Assumptions based on expected variations

Figure 5 shows the results of the sensitivity analysis; delivered cost was found to vary from \$77.12-\$85.36/dry ton (2016\$). The top five factors impacting uncertainty in the delivered cost included baling rate, interest rate, bale density, storage dry matter loss, and bale processor throughput; all of these except for interest rate are prior or current FT-funded R&D topics. Based on the observed variation, baling throughput is a key contributor to uncertainty, with its maximum value reducing the delivered feedstock by \$2.98/dry ton, whereas its minimum value would increase the delivered feedstock cost by \$5.26/dry ton. Additional parameters that had measurable effects on the uncertainty in delivered feedstock price included bale density, storage dry matter loss, and bale processor throughput. Uncertainties in interest rate, led to delivered cost ranges of -\$1.56/dry ton to +\$1.51/dry ton.

**Figure 5.** Tornado chart showing sensitivity of cost to operational parameters used to model the 2020 Herbaceous SOT Design. Values in the parenthesis represent the minimum, SOT and maximum value of each parameter for the different biomass sources.

### 3. INDUSTRIAL RELEVANCE OF THE BLENDSTOCKS

The availability of a biomass resource is not static, nor does it have a single definition. For the purposes of this report, availability is defined as the quantity of biomass materials that can be mobilized into the supply chain at a price that meets current cost targets. More specifically, resource availability assumed in this report is the quantity of three-pass and two-pass corn stover that can be purchased at average grower payments of \$21.71/dry ton and \$20.16/dry ton, respectively. The current availability of the blendstocks has been primarily determined through use of the 2016 Billion Ton Report. While BT16 primarily presents projections of how the market will develop based on sustained investment and technology improvement, the 2016 estimates in BT16 represented the currently economically available resources in the calendar year 2016. In 2016 it was estimated that there were 114,072,663 dry tons of corn stover available nationally, with 1,095,021 dry tons of corn stover within 100 miles of the study area. The region of interest for the 2020 herbaceous SOT remains the same as the 2019 SOTs, with the assumed biorefinery location in Sheridan County, KS. Northwest Kansas was chosen to demonstrate the barriers and cost of operating outside the niche, high-yield areas, which are more representative of yield conditions encountered when operating a national-scale bioenergy industry. However, the feedstock properties that are important to the conversion process, (i.e. ash, moisture, and carbohydrate content) were conservatively assumed to maintain applicability of the supply chain operations at a national scale.

### 4. QUALIFICATION OF THE BLENDSTOCKS FOR RENEWABLE IDENTIFICATION NUMBERS

The Environmental Protection Agency revised the National Renewable Fuel Standard Program to implement the requirements of the Energy Security and Independence Act of 2007 (EISA), in 2010. The revision of the program became known as RFS2 and mandated the use of 36 billion gallons of renewable fuel by 2022. As part of the revised rules, definitions of qualified biofuel feedstocks were outlined; the revised rules stipulated that “renewable fuels” had to be made from materials that qualify as renewable biomass. To be considered renewable biomass the materials must conform to the specified types and land types from where they are harvested as directed by EISA. From the final rule published in Vol 75, No. 58 of the Federal Register on page 14681.

*“The definition includes:*

- Planted crops and crop residue from agricultural land cleared prior to December 19, 2007 and actively managed or fallow on that date.*
- Planted trees and tree residue from tree plantations cleared prior to December 19, 2007 and actively managed on that date.*
- Animal waste material and byproducts.*
- Slash and pre-commercial thinnings from non-federal forestlands that are neither old-growth nor listed as critically imperiled or rare by a State Natural Heritage program.*
- Biomass cleared from the vicinity of buildings and other areas at risk of wildfire.*
- Algae.*

- *Separated yard waste and food waste.”*

Biochemical conversion focuses primarily on herbaceous materials. Specifically, the qualification must be examined for the three potential feedstock sources that were considered: corn stover, switchgrass and grass clippings.

Corn stover qualifies as a renewable material under Section II.B.4.a.i on page 14691. This section states that “... planted crops and crop residue harvested from agricultural land cleared or cultivated at any time prior to December 19, 2007, that is either actively managed or fallow, and non-forested.” This section goes on to further define both planted crops and crop residue. The definition of planted crops is the following:

*“All annual or perennial agricultural crops from existing agricultural land that may be used as feedstock for renewable fuel, such as grains, oilseeds, and sugarcane, as well as energy crops, such as switchgrass, prairie grass, duckweed and other species (but not including algae species or planted trees), providing that they were intentionally applied by humans to the ground, a growth medium, or a pond or tank, either by direct application as seed or plant, or through intentional natural seeding or vegetative propagation by mature plants introduced or left undisturbed for that purpose.”*

While crop residue is defined as the following:

*“The biomass left over from the harvesting or processing of planted crops from existing agricultural land and any biomass removed from existing agricultural land that facilitates crop management (including biomass removed from such lands in relation to invasive species control or fire management), whether or not the biomass includes any portion of a crop or crop plant.”*

In addition to the definitions of planted crops and crop residue, the qualification as a renewable material stipulates that the biomass must be harvested from “existing agricultural land”, which is limited to three land types: cropland, pastureland and Conservation Reserve Program land.

Cropland is defined for the purposes of EISA and RFS2 as, “land used for the production of crops for harvest, including cultivated cropland for row crops or close-grown crops and non-cultivated cropland for horticultural crops”. While pastureland is defined as, “land managed primarily for the production of indigenous or introduced forage plants for livestock grazing or hay production, and to prevent succession to other plant types.” Another caveat for the qualification of agricultural land is that the land must have been cleared or cultivated prior to December 19, 2007 and actively managed or fallow and non-forested since December 19, 2007. Under normal conditions, both corn stover and switchgrass will meet the conditions necessary to be deemed a renewable material and qualify for RINS.

Ultimately, the qualification of biomass as renewable is subject to verification that the feedstocks meet the requirements specified by EISA. Currently, there are three mechanisms that provide this verification. First, the individual fuel production facilities can perform their own recordkeeping and reporting. Second, renewable fuel producers can form a consortium that funds

third-party audit of quality assurance, based on an EPA approved plan. The final method only is only available to producers sourcing their biomass entirely from within the United States. This method uses an aggregate compliance approach using USDA publicly available data about agricultural land to form the basis of determination on feedstock renewability. In the case of non-agricultural products, producers must obtain enough documentation from their suppliers to prove compliance with EISA definitions.

## 5. 2020 Herbaceous n<sup>th</sup>-Supply SOT

As discussed above, in past SOTs we estimated farm-gate biomass availability based on yearly supply projections presented in the 2016 Billion-Ton Report (BT16) (DOE 2016b). This led to confounding of delivered cost reductions due to supply availability assumptions with cost reductions arising from BETO R&D investment. To eliminate this problem for the 2020 Herbaceous SOT presented above, we utilized the same supply curves used in the 2019 Herbaceous SOT (Roni et al. 2019a). In this section, we recast the 2020 Herbaceous SOT to utilize fixed n<sup>th</sup>-supply scenario supply curves for National and regional supplies of corn stover and switchgrass that will be used in all future Herbaceous SOTs. We refer to this recast SOT as the 2020 Herbaceous n<sup>th</sup>-Supply SOT.

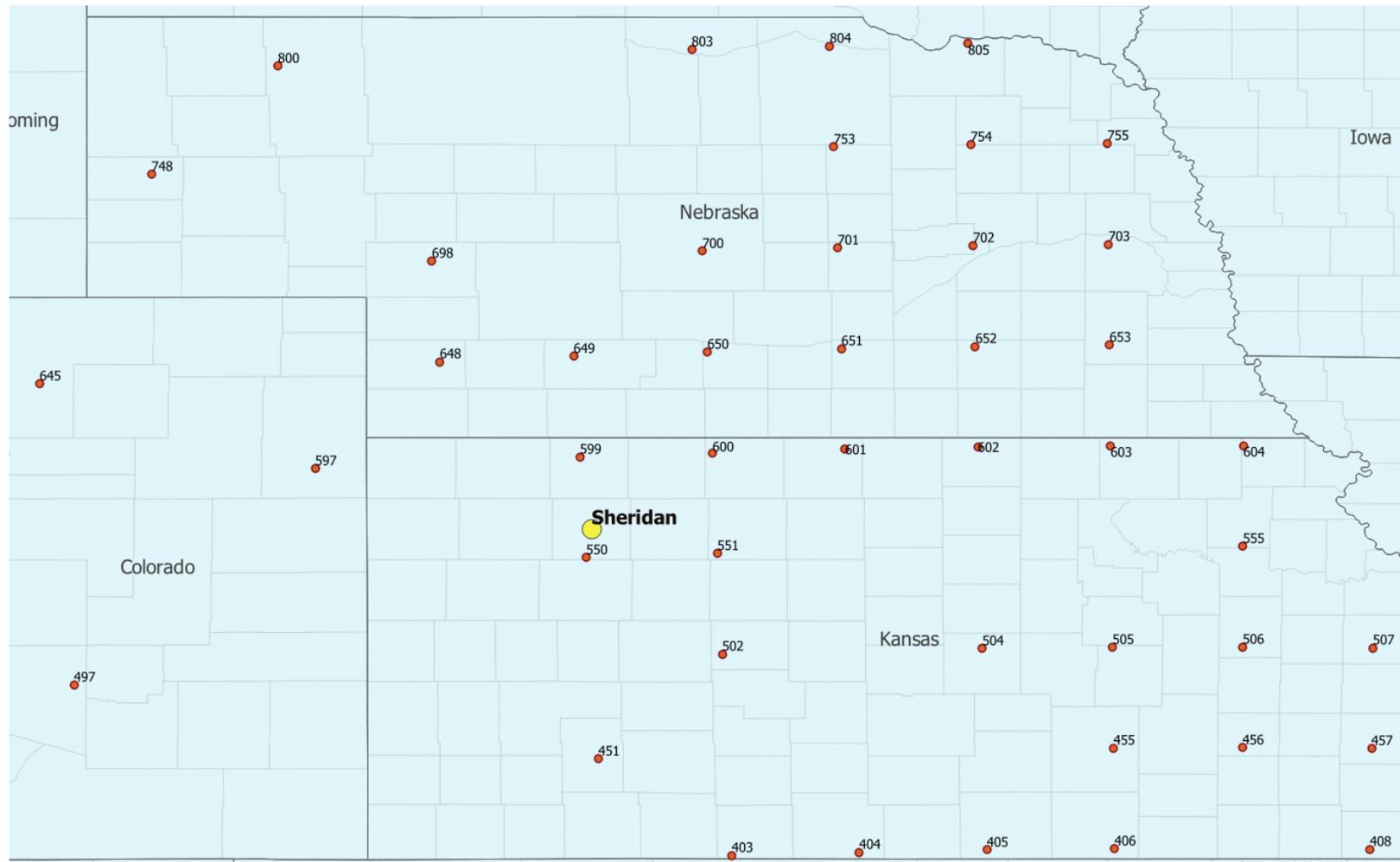
The n<sup>th</sup>-supply scenario was developed from a series of analyses developed jointly with ORNL (see Appendix B) and predicts optimal depot and biorefinery sites for corn stover and switchgrass supply in a demand-based supply in 2040. One impact of recasting the 2020 Herbaceous SOT to the n<sup>th</sup>-supply scenario is thus altering depot locations (and sizes) to align with the demand-based supply. For future SOTs these will remain fixed, allowing the SOTs to focus solely on the cost and quality impacts of BETO-funded technology advancements.

### 5.1 Resource Availability

Addressing biomass cost and quality targets is important to achieve the 2022 feedstock cost projection. Many of the targets are assumed to be for an n<sup>th</sup>-Plant (future) biorefinery, but feedstock cost and availability assumptions are based on present time projections of potential feedstock availability. To ensure consistency in analyses, analysts at INL and ORNL have defined a set of supply chain assumptions for an n<sup>th</sup>-Supply scenario and generated an updated resource availability for corn stover and switchgrass biomass feedstocks to supply n<sup>th</sup>-Plant biorefineries. A modified version of INL's Least-Cost Formulation model was developed to perform the analysis. A Mixed Integer Linear Programming (MILP) Model was used to locate 263 depot locations nationwide with delivered feedstock costs (corn stover and switchgrass) at less than \$79.07/ dry ton (2016\$) using corn stover and switchgrass biomass available in 2040 from BT16. The sited depot locations were used as inputs to the POLYSYS model to generate updated biomass availability maps (POLYSYS demand runs); biomass availability and depot/biorefinery locations used in this case are based on these POLYSYS demand runs. In the POLYSYS demand runs, the minimum grower payment for corn stover was set at \$30/dry ton based on the assumption that having existing depots in place would increase biomass demand

and thus reduce grower payments. Since this assumption is inconsistent with grower payment assumptions (minimum of \$40/dry ton) that were used to develop delivered cost targets for the 2022 Projection and the 2030 Design, we used \$40/dry ton as the minimum farm gate cost for corn stover (switchgrass remained unchanged). The assumptions, modelling approach and key results for the POLYSYS demand run are reproduced in Appendix B, as at the time of this writing they have not yet been published in the public domain in manuscript or external report form.

Logistic costs were estimated for the two potential depot locations (locations 550 and 551 shown in Figure 5) that are closest to Sheridan County in northwestern Kansas. The results showed that the minimized logistic cost for the two locations were similar, therefore, the geographic biorefinery location for the 2020 n<sup>th</sup>-Supply SOT case remains as Sheridan County, Kansas, which is unchanged from the 2019 Herbaceous SOT. It was assumed that all the biomass located in Kansas, Nebraska and Colorado would be potentially available to meet the demand of 725,000 dry tons delivered to the pretreatment reactor throat at the biorefinery.



**Figure 5.** The geographic area for the 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT. The red circles indicate potential depot locations that are used for the POLYSYS demand run. Location 550 is set as the biorefinery location for the 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT.

## 5.2 Logistics Costs

Results of the supply chain analysis are summarized in Table 8, which provides a detailed cost breakdown as well as greenhouse gas emissions. The greenhouse gas emissions analysis was completed by Argonne National Laboratory (ANL), using energy consumption and transportation distance data from the BLM. Table 9 compares modeled cost estimates for the herbaceous feedstock supply system for the 2019 Herbaceous SOT, 2020 Herbaceous SOT, 2020  $n^{\text{th}}$ -Supply SOT and the 2022 Herbaceous Projection.

**Table 8.** The 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT modeled cost and GHG estimates for an herbaceous feedstock supply system supplying 725,000 dry tons annually in northwestern Kansas. Design details are in Appendix A and the  $n^{\text{th}}$ -Supply scenario analysis and assumptions are reproduced in Appendix B.

Cost Element	Cost (\$/dry ton)			GHG emissions (kg CO <sub>2</sub> e/ton)
	Three-Pass Stover	Two-Pass Stover	Least-Cost Blend <sup>b</sup>	
<b>Blend Ratio</b>	29.63%	70.37%	100.00%	
<b>Grower payment</b>	\$21.71	\$20.16	\$20.62	
<b>Harvest and collection</b>	\$13.84	\$18.79	\$17.33	11.17
<b>Storage and queuing</b>	\$6.66	\$6.74	\$6.72	2.50
<b>Transportation and handling</b>	\$11.66	\$13.74	\$13.12	14.00
<b>In-plant receiving and preprocessing</b>	\$19.60	\$19.60	\$19.60	47.21
<b>Dockage</b>	\$2.59	\$0.89	\$1.39	
<b>Total</b>	<b>\$76.06</b>	<b>\$79.92</b>	<b>\$78.78</b>	<b>74.88</b>

a Pesticide and fertilizer emissions incurred during biomass production were attributed to the biomass growth stage of the life cycle and are not included.

b The blend costs are presented as the weighted average of the blend component costs.

c Grower payment taken as the cost assumed for procurement of grass clippings.

**Table 9.** Summary of modeled cost estimates for the herbaceous feedstock supply system for biochemical conversion pathway for the 2019 SOT, 2020 SOT, 2020 <sup>n<sup>th</sup></sup>-Supply SOT and 2022 Projection.

	2019 SOT	2020 SOT	2020 <sup>n<sup>th</sup></sup> -Supply SOT	2022 Projection
<b>Feedstock</b>	<b>Blend</b>	<b>Blend</b>	<b>Blend</b>	<b>Blend</b>
<b>Net delivered cost (\$/dry ton)</b>	<b>\$81.37</b>	<b>\$80.10</b>	<b>\$78.78</b>	<b>\$79.07</b>
Grower payment (\$/dry ton)	\$20.56	\$20.62	\$20.62	\$22.37
<b>Feedstock logistics (\$/dry ton)</b>	<b>\$60.81</b>	<b>\$59.47</b>	<b>\$58.16</b>	<b>\$56.70</b>
Harvest & collection (\$/dry ton)	\$17.14	\$17.33	\$17.33	\$12.79
Storage & queuing (\$/dry ton)	\$6.49	\$6.72	\$6.72	\$8.35
Preprocessing (\$/dry ton)	\$20.84	\$19.43	\$19.60	\$21.44
Transportation & handling (\$/dry ton)	\$14.76	\$14.61	\$13.12	\$12.44
Dockage (\$/dry ton)	\$1.58	\$1.39	\$1.39	\$1.68

In the 2020 Herbaceous <sup>n<sup>th</sup></sup>-Supply SOT, the technologies, biomass physical and chemical quality parameters, and process flows are identical to those used in the analysis presented Section 2 for the 2020 Herbaceous SOT presented in Section 2. As a result, the delivered quantities and compositions of the biomass sources, the preprocessed blendstocks produced and the least-cost blend are the same as in the 2020 Herbaceous SOT. Due to the higher biomass availability in the POLYSYS demand run, a lower transportation cost is estimated for the 2020 Herbaceous <sup>n<sup>th</sup></sup>-Supply SOT. There is a small increase of \$0.17/dry ton in the depot construction cost compared to the 2020 Herbaceous SOT because of differences in depot size. Overall, by incorporating the biomass availability and depot locations optimized or the demand-based supply from the POLYSYS demand runs, the delivered feedstock cost is decreased by \$1.31/dry ton. Noting that this brings the delivered cost below the 2022 Herbaceous Projection which was based on projected 2022 supply curves from BT-16, it will be necessary to recast the 2022 Herbaceous Projection to the <sup>n<sup>th</sup></sup>-supply scenario during FY21 to put them on the same supply basis for comparison. It will also be necessary in the future to recast the 2030 Herbaceous Projection of \$71.26/dry ton (2016\$) to bring the SOTs and targets to the same supply basis.

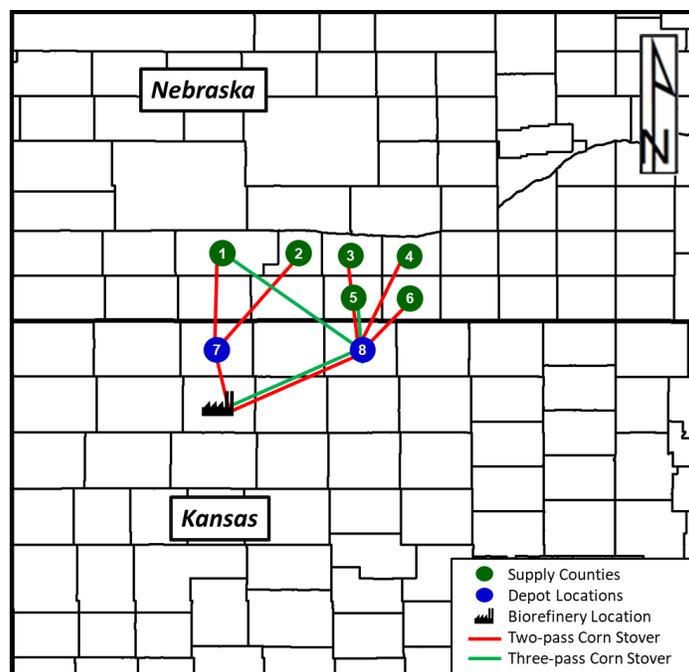
The <sup>n<sup>th</sup></sup>-supply scenario depot locations, biomass source counties and biorefinery location are listed in Tables 10 and 11 and are shown pictorially in Figure 6. The least cost supply chain network utilized two distributed depots (Nodes 7 and 8 in Figure 6) for a biorefinery located in Sheridan County, Kansas. Because of the higher biomass availability around Node 8, the depot at Node 8 is sized larger than the one at Node 7. In order not to exceed the capacity of depot in Node 7, three-pass corn stover purchased from Node 1 is delivered to the depot in Node 8. The results also show that a biorefinery with a design capacity of 725,000 dry tons/year, would need to procure at least 811,180 dry tons of biomass annually to account for losses in the system. This procured biomass is 29,487 dry tons less than the 2019 Herbaceous SOT.

**Table 10.** Node IDs and county names for the biomass source counties for the supply system depicted in Figure 5 for the 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT. Decatur County, KS and Phillips County, KS are not identified in the table because they are depot locations but not farm-gate sources of biomass.

Node	County
-	Sheridan County, KS
1	Frontier County, NE
2	Gosper County, NE
3	Phelps County, NE
4	Kearney County, NE
5	Harlan County, NE
6	Franklin County, NE

**Table 11.** Locations and sizes of distributed depots for least cost delivery of 725,000 dry tons/year of blended feedstock to Sheridan County, KS for the 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT. Source nodes are identified by county name in Table 9 and are shown geographically in Figure 6.

Node	Identifier	County	Capacity (dry tons/yr)	Biomass Type	Biomass Source Nodes
-	Biorefinery	Sheridan, KS	725,000	Blend	7, 8
7	Depot	Decatur, KS	195,315	two-pass corn stover	1, 2
8	Depot	Phillips, KS	529,685	three-pass corn stover	1, 5
				two-pass corn stover	3, 4, 6



**Figure 6.** Supply chain network design for the 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT. The supply chain has 2 distributed depots (Nodes = 7 and 8) with the biorefinery located in Sheridan County, Kansas. Three-pass corn stover is sourced from Nodes 1 and 5. Two-pass corn stover is sourced from Nodes 1, 2, 3, 4 and 6. County names are shown with their node identifiers in Table 9 and Table 10.

### 5.3 Sensitivity Analysis of Costs

The total delivered cost was found to vary in the range from \$75.80-\$84.04/dry ton (2016\$). Because the technologies, critical processes, and key operational parameters for the 2020 Herbaceous  $n^{\text{th}}$ -Supply SOT design scenario are the same as for the 2020 Herbaceous SOT presented in Section 2, the key contributors to uncertainty and the uncertainly ranges are identical to those presented in Figure 4.

## 6. SUMMARY

The Feedstock Technologies platform within BETO focuses on (1) reducing the delivered cost of sustainably produced biomass; (2) preserving and improving the physical and chemical quality parameters of harvested biomass to meet the individual needs of biorefineries and other biomass users; and (3) expanding the quantity of feedstock materials accessible to the bioenergy industry. To support BETO and its bioenergy production goals, INL completes annual SOT reports for herbaceous and woody biomass feedstock logistics. This report provides the status of

technology development of feedstock logistics for herbaceous biomass to biofuels utilizing experiment-based data and results and provides a relative comparison to technical targets and costs goals from design cases.

Although CFSS forms the backbone of the emerging biofuels industry, they have limitations that restrict widespread implementation on a national scale. To meet the demands of the future industry, the feedstock supply system must shift from the conventional system to what has been termed “advanced” supply systems. In advanced designs, a distributed network of aggregation and processing centers, termed “depots,” are employed near the points of biomass production (i.e., the field or forest) to reduce feedstock variability and produce feedstocks of a uniform format, moving toward biomass commoditization. The 2020 Herbaceous SOT is part of a longer-term vision of achieving an implemented advanced feedstock supply system, which produces a stable, tradable commodity at the decentralized distributed depot.

The 2020 Herbaceous SOT incorporates an actively managed storage system for early-harvested bales which are typically > 30% moisture. The storage system utilizes a combination of best management practices and “farm-scale technologies” such as enhanced in-storage drying to achieve storage stability objectives. A wrapped-bale mechanical ventilation concept for these very wet bales utilizes a combination of microbial self-heating and advective air flow (supplied by a commercial grain dryer blower) to reduce stack moisture from 30% to <20% in 30 days. This technical improvement positively affects storage dry matter loss and feedstock preprocessing performance within the feedstock logistics system.

Previous SOT results have confounded biomass supply assumptions from BT-16 that predicted an increasing supply year on year. To get a clearer presentation of cost impacts of technology improvements, for the 2020 SOT we utilized the same supply curves from BT-16 that were used for the 2019 SOT. The 2020 Herbaceous SOT report documents the current modeled cost of an herbaceous feedstock supply system from harvest to the pretreatment reactor throat for hydrocarbon fuel production via biochemical conversion, based on equipment and processes now available or potentially available in the near term. The modeled cost also considers both the required quality and the availability of the biomass resources. The 2020 Herbaceous SOT predicts a modeled delivered feedstock cost of \$80.10/dry ton (2016\$); this is a \$1.27/dry ton (2016\$) decrease from the 2019 Herbaceous SOT. Technology improvements that contributed to this modeled cost reduction include reduced cost in the feedstock preprocessing caused by reduced moisture from the newly designed field side storage. A greenhouse gas emissions (GHG) assessment was completed by Argonne National Laboratory using the 2020 Greenhouse Gases, Regulated Emissions, and Energy use in Transportation model (GREET), estimating a decrease of up to 6.68 kg CO<sub>2</sub>e/ton from the 2019 SOT (84.16 kg CO<sub>2</sub>e/ton in the 2019 SOT to 77.48 kg CO<sub>2</sub>e/ton in the 2020 Herbaceous Feedstock SOT). This net reduction is attributed to reduced energy consumption in the hammer mill, reduced high emission feedstock used in the blend (less three-pass corn stover), and incorporation of the updated GREET model.

Moving forward in future years, we will implement use of the <sup>n</sup><sup>th</sup>-supply scenario developed in FY19 and FY20 as a constant supply in order to focus on improvements due to BETO-funded technology improvements. Hence, in this report we also present the 2020 Herbaceous SOT recast using the supply curves and optimal depot and biorefinery locations

determined for the n<sup>th</sup>-supply scenario (see Appendix B); this is presented in this report as the 2020 Herbaceous n<sup>th</sup>-Supply SOT. Overall, by incorporating the biomass availability and depot locations optimized or the demand-based supply from the POLYSYS demand runs, the delivered feedstock cost was decreased by \$1.31/dry ton. Noting that this brings the delivered cost below the 2022 Herbaceous Projection which was based on projected 2022 supply curves from BT-16, it will be necessary to recast the 2022 Herbaceous Projection to the n<sup>th</sup>-supply scenario during FY21 to put them on the same supply basis for comparison. It will also be necessary in the future to recast the 2030 Herbaceous Projection of \$71.26/dry ton (2016\$) to bring the SOTs and targets to the same supply basis.

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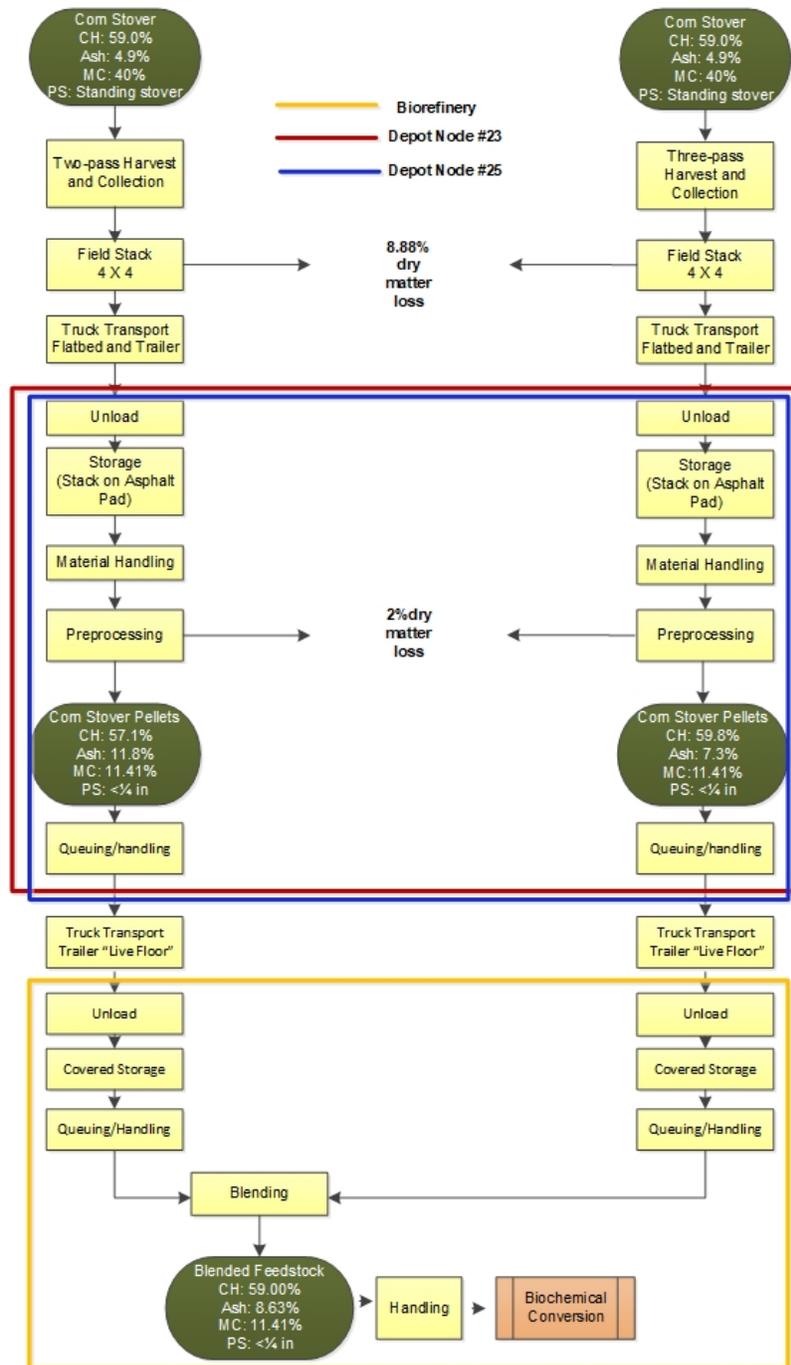
## **APPENDIX A – 2020 Herbaceous State of Technology Feedstocks Logistics Design and Assumptions**

The 2020 Herbaceous SOT provides an annual herbaceous feedstock supply to a biorefinery located in Sheridan County, Kansas (northwestern Kansas) consisting of 725,000 dry tons of an herbaceous biomass blend comprised of 29.63% three-pass stover and 70.37% two-pass stover. The 2020 Herbaceous SOT incorporates two depots (identified as Nodes 23 and 25 in Figure 4 and Table 5 of the main document, and Figure A-1 in this appendix).

The 2020 Herbaceous SOT couples feedstock logistics with resource availability, reflected as grower payment, to estimate the delivered feedstock cost required to supply the biorefinery. The design is located in an area of relatively low biomass productivity, consistent with the 2013-2019 Herbaceous SOTs, to conservatively include the barriers and cost implications for meeting national targets for a national scale biorefinery industry. When biomass must be sourced in locations where there is insufficient biomass supply at the specified quality but there is also a diversity of biomass types available, blending options become available to assist in meeting conversion quality specifications. Grower payments were calculated from farm gate prices by subtracting modeled harvest and collection costs and scaling to the appropriate year.

The three-pass corn stover harvest and collection method modeled in this analysis is consistent with those used in conventional systems referred to as “multi-pass harvesting systems.” The two-pass corn stover harvesting and collection method modeled is an advanced harvest method that has been utilized by Poet-DSM to harvest corn stover for its Emmetsburg, IA facility. In this method, the first pass is grain harvest using a combine with header raised to just below the ear on the corn stalks and the spreader turned off, and the second pass is a baler (Birrell et al. 2014; Shinnars et al. 2012). This eliminates the windrowing step, which is a significant source of soil entrainment in the baled corn stover. The raised header (higher cut height) leads to a lower harvest yield and is generally a conservative approach to ensure soil sustainability. The three-pass stover and two-pass stover are harvested, collected, and then stored field-side (tarpred) until being transported by truck to the main depot in bales.

The modeled supply chain for the 2020 Herbaceous SOT utilizes general purpose depots in the sense that they employ identical preprocessing equipment in each, and can receive any of the sources of stover or switchgrass (see Table 6 and Figure A-1). The baled biomass delivered from road-side storage at the farm gates of the supplying counties is size reduced using hammer milling/fractional milling, densified using high moisture pelleting, and then cooled and placed into temporary depot storage until shipping to the biorefinery when needed. Pellets shipped from these depots to the biorefinery are placed into silos (separated by biomass type) when received and blended to the correct ratio immediately prior to feeding to the reactor throat. The silos serve as the metering bin for the conversion process, as the pellets are blended as they are conveyed to the feeding system for the pretreatment reactor.



**Figure A-1.** The modeled 2020 Herbaceous SOT feedstock supply system. CH=Carbohydrate content, MC = moisture content, PS=Particle size. Depots are identified as nodes 23 and 25. Optimal locations and sizes of these nodes are listed in Figure 3 and Table 5 and 6 of the main body of this report.

## Resource Availability

The geographic area chosen for the 2020 Herbaceous SOT is northwestern Kansas, with the biorefinery located in Sheridan County. It was assumed that all corn stover and switchgrass biomass as identified in the BT16 report located in Kansas, Nebraska and Colorado would be potentially available to meet the demand of 725,000 dry tons delivered to the pretreatment reactor throat at the biorefinery. The available corn stover was estimated from the 2019 county-level data in the BT16 report (DOE 2016b) and modified through implementation of the ILM strategy (Roni et al. 2019a). Corn stover availability in BT16 is representative of conventional three-pass harvesting. We assumed that two-pass harvesting would be limited to high-yielding counties (defined as stover yields  $\geq 2.0$  dry tons/acre), however, three-pass harvesting could also be utilized in these counties. We further assumed that only three-pass harvesting would be used in low-yielding counties (stover yields  $< 2.0$  tons/acre). This was done to maximize yields of corn stover from the low-yielding counties, which are significantly greater in number than high-yielding counties.

Because two-pass harvesting cuts higher on the stalk, less stover is collected by the baler. In a multi-year study, Birrell et al. (2014) showed that two-pass harvest of material other than grain (MOG) reached about 35% of the collection efficiency of conventional three-pass harvest. In another study (Smith et al. 2014), it was observed that the specific two-pass harvest method assumed in this SOT achieved slightly less than half the yield observed for the flail shred three-pass harvest method assumed for this study (Table A-1). Three-pass harvesting with a flail shredder and square bales achieved 1.9-2.0 dry tons/acre, while the two-pass system achieved 0.9-1.0 dry tons per acre. The average ratio of two-pass yield/three-pass yield is then 0.487. Hence, for the high-yielding counties, we adjusted the BT16 three-pass availabilities for corn stover down by a factor of 0.487 to give the two-pass availability numbers for the analysis.

**Table A-1.** Baled corn stover yield and mean ash contents in three-pass harvesting (Rake, Flail), and two-pass harvesting (MOG) (Smith et al. 2014). We assumed square bales for transportation; relevant treatments in the table are in **bolded** text. The flail treatment (ISU '12 3.2) was not used because its low ash content is inconsistent with the other flail treatments.

Windrow	Bale Type	ID	Yield (DMT/acre)	Ash (wt% db)
MOG <sup>a</sup>	Round	MOG-1	0.5	4.9
MOG	Round	MOG-2	0.6	3.8
MOG	Round	MOG-3	0.7	7.6
MOG	Round	MOG-4	0.7	6.8
MOG	Round	MOG-5	0.7	5.6
MOG	Round	MOG-6	0.8	6.3
<b>MOG</b>	<b>Square</b>	<b>MOG-7</b>	<b>0.9</b>	<b>5.8</b>
<b>MOG</b>	<b>Square</b>	<b>MOG-8</b>	<b>1.0</b>	<b>5.3</b>
Rake	Square	RAKE-1 <sup>b</sup>	0.9 <sup>b</sup>	8.1
Rake	Square	RAKE-2 <sup>b</sup>	1.4 <sup>b</sup>	7.6
G-hoff	Square	G-HOF	1.9	8.0
1-P	Square	1-PASS <sup>c</sup>	1.9	5.7
<b>Flail</b>	<b>Square</b>	<b>FLAIL<sup>c</sup></b>	<b>2.0</b>	<b>13.9</b>
Rake	Square	ISU '12 3.1	1.4	14.6
Flail	Square	ISU '12 3.2	1.4	7.6
Rake	Square	ISU '12 3.3	1.9	15.6
<b>Flail</b>	<b>Square</b>	<b>ISU '12 3.4</b>	<b>1.9</b>	<b>12.1</b>

a The combine drops the material other than grain (MOG) into a loose windrow, which is followed by a separate baler. Drawbacks to this method are reduced collection efficiency and field “striping” as a result of uneven residue removal.

b Assumed average bale weight from previous co-located studies

c Provided by Matt Darr, Iowa State University

## Process Design and Cost Estimation Details

In this section, the costs of different supply chain operations are described along with key assumptions and input parameters.

### A.1 Interest Rate and Energy Cost Assumptions

The 2020 Herbaceous SOT uses the same interest rate and energy cost assumptions used for the 2019 Herbaceous SOT as shown in Table A-2.

*Table A-2. Energy prices and interest rates used to model herbaceous feedstock logistics costs for the 2020 Herbaceous SOT.*

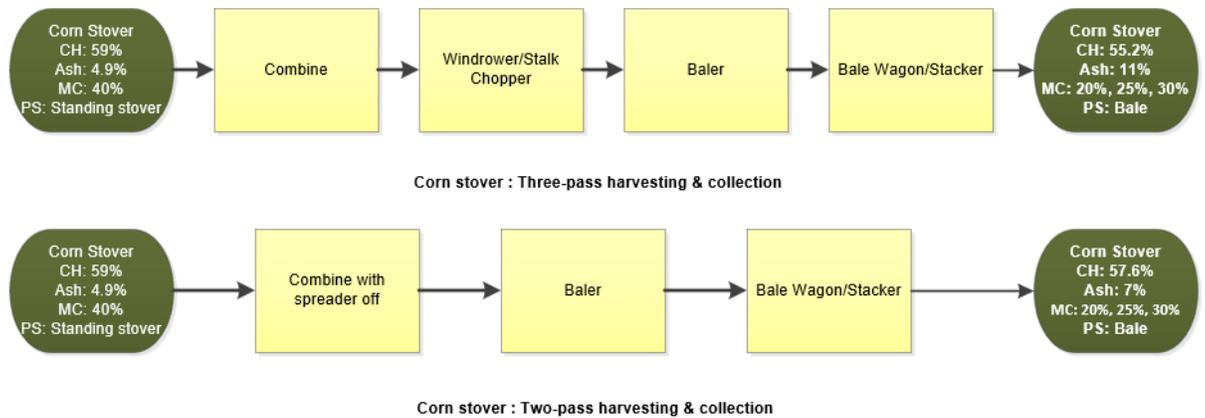
Component	2019 Assumptions	2020 Assumptions
Interest Rate	8% <sup>a</sup>	8% <sup>a</sup>
Electricity Price	\$0.0672/kWh <sup>b</sup>	\$0.0672/kWh <sup>b</sup>
Natural Gas Price	\$3.36/MMBtu <sup>b</sup>	\$3.36/MMBtu <sup>b</sup>
Off-Road Diesel Price	\$2.011/gal <sup>b</sup>	\$2.011/gal <sup>b</sup>

a See Jones et al. (2013)

b See EIA (2018). Updated from the 2018 Herbaceous SOT using the Producer Price Index

### A.2 Harvest and Collection

Although switchgrass was included in the available biomass sources, the optimized 2020 Herbaceous SOT design utilizes only corn stover biomass. Corn stover harvest is assumed to be available via two different harvesting methods, three-pass (conventional) harvesting and two-pass harvesting (advanced). Conventional three-pass harvesting has the advantage of high yield, but the disadvantage of low quality with respect to carbohydrates (lower) and ash (higher). Two-pass harvesting allows better quality but decreases the harvesting yield. Conventional three-pass systems involve cutting the feedstock, collecting the material into a windrow, and then baling the windrowed material (Figure A-2). The two-pass collection method eliminates the windrowing step and thereby reduces the potential for soil contamination (Shinners et al. 2012, Birrell et al. 2014). In this method, the combine drops the material other than grain (MOG) into a loose windrow, which is followed by a separate baler. The two-pass method assumed here has been utilized by POET-DSM's Advanced Biofuels' Project Liberty. Drawbacks to this method are reduced collection efficiency (due to a higher cut height) and field "striping" (Birrell et al. 2014) as a result of uneven residue removal. Two-pass collection does not increase the required throughput to the combine or hinder its operation but requires some minor operational modifications. Combine operation is altered by disengaging the straw choppers at the rear of the combine to allow the MOG to drop behind the combine into a loose windrow. The combine is modified by adding "stalk-stompers" or by mounting rollers under the header to bend the lower stalk over in the rows on which the MOG will be dropped. These devices are commonly (but not universally) used under the wheel-track rows to reduce the risk of tire punctures. They are optional equipment but are relatively inexpensive.



**Figure A-2.** The 2020 Herbaceous SOT harvest and collection operations for corn stover. It is assumed that prior to baling there is some amount of field, 50% of the total biomass will reach 25% moisture, 25% of the biomass will reach 20% moisture, and the remaining 25% of the biomass will reach 30% moisture. CH=Carbohydrate content, MC = moisture content, and PS=Particle size.

Because of the higher cutting height in two-pass harvest, the stover yields are limited to the upper stalk, husk, cob, and some leaves, which (stated above) amount to about, or less than, 1 ton/acre. However, it has been shown that two-pass MOG is lower in moisture and ash content (Hoskinson et al. 2007). Most of the ash variability is introduced from soil during baling. Corn stover yield could be potentially increased in the two-pass harvest and collection method by cutting stover lower in the stalk. This could be accomplished by using a stalk-chopping head, reducing the cutting height. However, with lower stalk comes more moisture and ash and the stalk chopping head requires more power and increases cost.

It was assumed that two-pass harvesting will be limited to high-yielding areas as a result of this stover yield limitation. Our reasoning is as follows: Pordesimo et al. (2005) demonstrated that at grain maturity, the above ground stover mass fraction is approximately equal to the grain mass, in that case 6.7 dry tons/acre and 207 bushels/acre for the stover and the grain, respectively. In a multi-year study (Birrell et al. 2014), two-pass baling resulted in 35% stover yield with 186 bushels/acre grain yield. To recover 0.7 dry tons/acre (the experimentally-validated average two-pass yield used for estimating harvesting costs for two-pass harvest; see Table A-4) or more, it would be necessary to have grain yields of 372 bushels/acre, which is unlikely on low-yielding fields. This represents an average yield in the Corn Belt, meaning that half of the available fields will have yields below this value, thus, corn stover yields less than 0.7 dry tons/acre. Part of the quality benefit from two-pass harvest arises from lower levels of inorganics higher up the stalk. Hoskinson et al. (2007) showed elevated inorganic nutrient and total ash contents in the lower stalk materials relative to the upper stalk. Additionally, an analysis by Birrell et al. (2014) showed that a greater quantity of ash forming minerals (Al, B, Cu, Fe, Mn) were present in multi-pass bales relative to two-pass MOG bales collected from the same experimental plots. Hence, while upper stalk collection via two-pass baling yields less stover, the

total ash content of the stover is lower, and there is a sustainability benefit since inorganic nutrient removal from the field is lower as well.

Table A-3 summarizes the harvest and collection design assumptions for the 2020 Herbaceous SOT. The assumed yield, capacity and efficiency of harvest and collections equipment, moisture content, and ash content were estimated based on published data (Anderson et al. 2013, Lindsey et al. 2013, Bonner et al. 2014, DOE 2016b, Owens et al. 2016), data from field trials (Smith et al. 2012, Smith et al. 2014, Brue et al. 2015), data taken from the INL Bioenergy Feedstock Library (INL 2016), and from personal communications<sup>1,2</sup>.

*Table A-3. Harvest and collection design assumptions in the 2020 Herbaceous SOT for three-pass corn stover and two-pass corn stover.*

Component	Corn stover	
	Three-Pass Harvest	Two-Pass Harvest
<b>Harvest time</b>		
Operational hours	6 weeks/year, 6 days/week, 14 hour/days	6 weeks/year, 6 days/week, 14 hour/days
<b>Combine</b>		
Capacity	41 tons/hour	41 tons/hour
Field efficiency	70%	70%
Collection efficiency	43%	43%
<b>Stalk chopping windrower</b>		
Capacity	11.5 acres/hour	N/A <sup>a</sup>
Efficiency	80%	N/A
<b>Bale wagon/stacker</b>		
Capacity	12 bales/load	12 bales/load
<b>Baler</b>		
Capacity	50 bales/hour	25 bales/hour
<b>Harvest yield</b>		
Harvest yield	1.2 tons/acre	0.7 tons/acre

a N/A, not applicable.

### A.3 Storage

The 2020 Herbaceous SOT incorporates an actively managed storage system comprised of a combination of best management practices and “farm-scale technologies” such as enhanced

<sup>1</sup> Personal communication from Magen E. Shedden, a researcher at Oak Ridge National Laboratory (ORNL)

<sup>2</sup> Personal communication from William Smith, INL researcher

in-storage drying to achieve storage stability objectives. Storage research (WBS 1.2.1.1) evaluated modeled operational performance of actively managed storage systems. This actively storage managed storage consists of a microbial self-heating and advective flow system, supplied by a commercial grain dryer blower. Experimental results from the bale dryer (Fig. 2 in the main document) show that a single bale can be dried from 30% moisture to <20% in two to four days, which implies that a stack that is 12 bales in length could be dried in 30 days. Drying experiments (Smith and Plummer, 2020) performed in INL’s storage simulators showed that stover can be dried from 30% to 20% moisture at a range of flow rates with and incur dry matter losses of 5% or less. The primary factors that drive biological dry matter loss are moisture content of the biomass entering storage, the temperature and relative humidity as a function of time, oxygen availability, pH, and the presence of inhibitory compounds in the biomass extractives component.

As the actively managed storage system only applies to the early harvested high moisture biomass, the 2020 Herbaceous SOT assumes that the moisture content of biomass prior to storage is distributed as follows: 25% of the biomass has 30% initial moisture (early harvested bales), 50% of the biomass has 25% initial moisture (bales harvested during the middle 50% of the harvest window), and the remaining 25% of the biomass has 20% initial moisture (late harvested bales). In the 2020 Herbaceous SOT, the dry matter losses are partitioned to individual corn stover components using the average observed losses of individual corn stover components during 3-month storage tests (Wendt et al. 2013) in the INL storage simulators at initial moisture contents ranging from 20-52%. Tables A-4 and A-5 summarize dry matter loss and storage design assumptions applied in the 2020 Herbaceous SOT.

**Table A-4.** Average distribution of dry matter losses among corn stover components by initial moisture content.

Biomass moisture content distribution		DML after field storage
% of the total biomass weight	Initial Moisture content	
25.00%	20.00%	7.70%
50.00%	25.00%	11.40%
25.00%	30.00%	5.00% <sup>a</sup>

<sup>a</sup> Smith and Plummer, 2020

**Table A-5.** Field storage design assumptions for the 2020 Herbaceous SOT.

Component	Storage TEA parameters 1	Storage TEA parameters 2	Storage TEA parameters 3
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<b>Storage moisture content</b>	30%	25%	20%
<b>Storage dry matter loss</b>	5.0%	11.4%	7.7%
<b>Storage moisture loss</b>	10%	5%	0%
<b>Stack configuration</b>	3x12 wrapped stack	4 x 4 tarped	4 x 4 tarped
<b>Dryer Cost Basis<sup>a</sup></b>	\$3.11/dry ton <sup>b</sup>	-	-

(Dryer model: GSI 5-hp model GGI-80711)

<sup>a</sup> Dryer is used during daylight only.

<sup>b</sup> Smith and Plummer (2020).

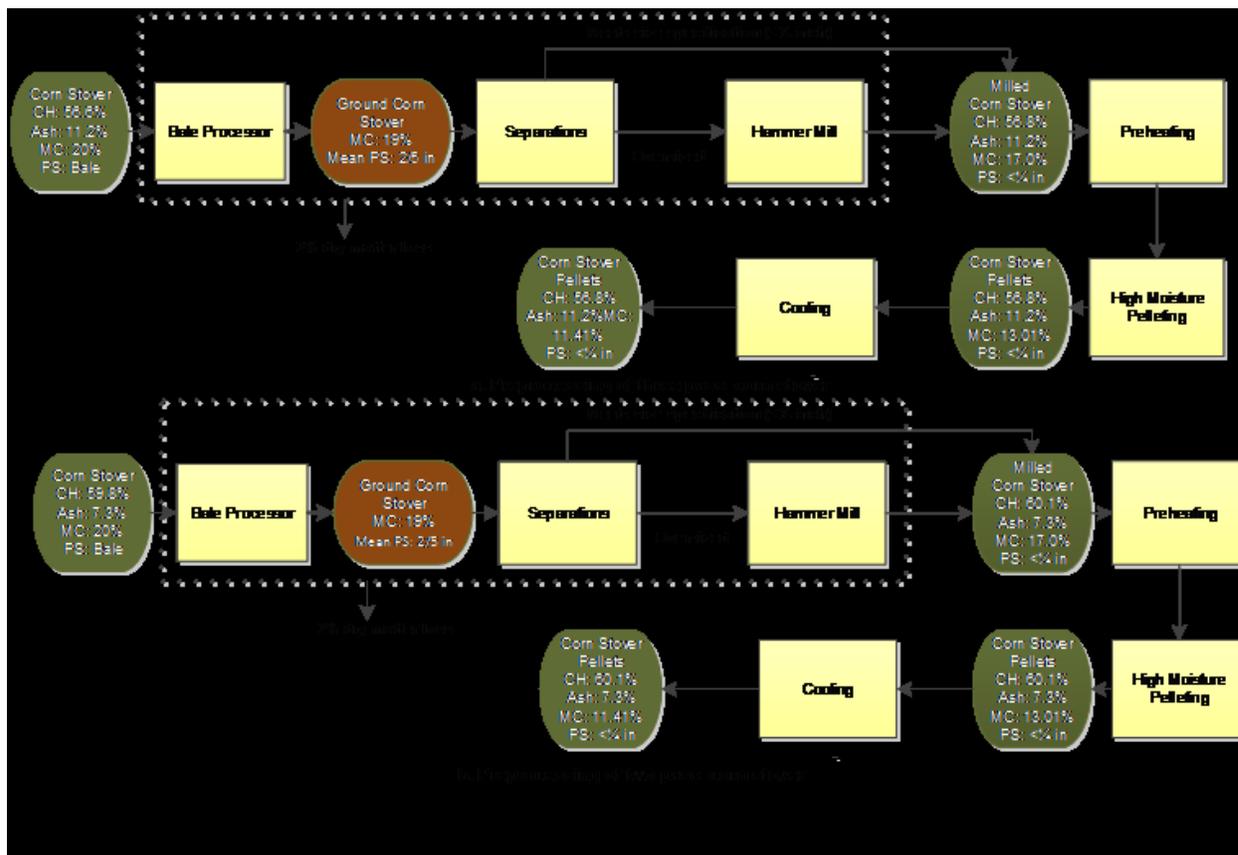
#### A.4 Preprocessing

The preprocessing technology in the 2020 Herbaceous SOT is identical to that utilized in the 2019 Herbaceous SOT. However, the preprocessing operating conditions and performance were updated based on the biomass properties exiting the new storage design. For example, since the biomass coming from storage will have lower moisture than the 2019 Herbaceous SOT, the hammer mill will consume less energy and will have higher throughput. Hence, the hammer mill performance has been updated in the 2020 Herbaceous SOT.

The 2020 Herbaceous SOT design utilizes high moisture pelleting in corn stover preprocessing. In high moisture pelleting, the biomass is preheated to approximately 110°C for short durations (typically 5 min) prior to pelleting. Depending on the temperature used, preconditioning biomass by preheating it can affect both its chemical composition and its behavior during mechanical densification processes such as pelleting. When these changes impact mechanical properties, thereby changing the way the feedstock responds during densification, the overall quality of the pellets can be improved (Bhattacharya et al. 1989, Tumuluru et al. 2010). Preheating can also increase the throughput of the pellet mill and reduce the energy requirement per kilogram of biomass pellets produced. When the preheat temperature is high enough to impact chemical composition, preheating can also enable production of higher-quality densified products for multiple end-use applications (Aqa et al. 1992, Bhattacharya 1993). Preheating in the presence of moisture can also promote softening of the natural binders in the biomass, including starch, lignin, and protein (Tumuluru 2014). Laboratory experiments performed under INL WBS 1.2.1.2 using flat-die and round-die pellet mills has shown that high durability pellets can be produced at an intermediate moisture content of 33-34% (wet basis), preheating temperatures > 70°C, and die speeds > 50 Hz (Tumuluru 2014).

As in the 2019 Herbaceous SOT, the 2020 Herbaceous SOT eliminates the drying step during preprocessing of corn stover. Pilot-scale testing of high moisture pelleting and cooling performed under INL WBS 1.2.1.2 indicated that the conservative moisture loss assumptions used in 2016 during grinding and pelleting could be increased, which eliminated the need for drying the pelleted biomass. Reduced energy consumption for high moisture pelleting was also observed in the pilot-scale ring die pellet mill tests, as compared to the lab-scale flat die pellet mill values utilized in the 2016 Herbaceous SOT.

The 2020 Herbaceous SOT utilizes the same percentage of material bypassed during fractional milling as 2019. As shown in Figure A-3, fractional milling inserts a screening operation (disk screen) between the first stage and second-stage size reduction operations (the bale processor and hammer mill, respectively) to remove the material that already meets the size



**Figure A-3.** 2020 Herbaceous SOT preprocessing configurations for corn stover. CH=Carbohydrate content, MC = moisture content, PS = particle size

specification before the material enters second-stage comminution. This reduces the amount of material that flows through the second-stage comminution, thereby reducing its size (cost) and energy consumption. In addition, fewer fines are produced because the material already meeting the particle size specification is not further size reduced. Hence, a tighter particle size distribution is achieved. Particle size distribution analysis shows that 30% of the corn stover material meets particle size requirements after the first-stage grinder and can bypass the second-stage size reduction, thereby leading to significant savings. Experiments performed in the Biomass Feedstock User Facility (BFNUF) at INL (WBS 1.2.3.3) have shown that 1-2% of feedstock dry matter that arrives at the biorefinery gate is lost as dust during grinding, of which as much as 25% is ash.<sup>3</sup> The organic fraction is generally comprised of fines generated from the

<sup>3</sup> Personal communication regarding dust collection during preprocessing from Neal Yancey, INL researcher

leaves, which are thin and brittle and shatter from the hammer impacts during grinding.

Corn stover preprocessing for the 2020 Herbaceous SOT design is shown above in Figure A-3(a) for three-pass corn stover preprocessing, and Figure A-3(b) for two-pass harvesting. Although the preprocessing operations are identical for both corn stover sources, they have been shown separately because their initial and intermediate moisture contents and compositions are different (these are shown at various stages within the figures). Input parameters (such as throughput and energy consumption) have been updated in Table A-6 for corn stover, based on pilot-scale results (WBS 1.2.1.2).

**Table A-6.** Summary of 2020 Herbaceous SOT preprocessing assumptions. The benefit of fractional milling is included by adjusting the throughput and energy consumption of 2nd stage size reduction.

Component	Three-Pass & Two-Pass Corn Stover
<b>Location of operation</b>	Depot Nodes 23 and 25
<b>Stage 1 size reduction</b>	
Grinder type	Bale processor
Screen Size (inch)	NA
Energy (kWh/dry ton)	8
Throughput (dry ton/hour/machine)	10
Operating conditions (moisture %)	20.0%
<b>Separations</b>	
Screen type	Disc Screen
Energy (kWh/dry ton)	Minimal electricity
Throughput (dry ton/hour/machine)	10
Operating conditions (moisture %)	19.0%
Bypass	30%
<b>Stage 2 Grinder</b>	
Comminution method	Hammer mill
Screen Size ( inch)	0.25
Energy (kWh/dry ton)	50 (35 <sup>a</sup> )
Throughput (dry ton/hour/machine)	2.04 (2.92)
Operating conditions (moisture %)	19.0%

**Table A-6.** (continued)

Component	Three-Pass & Two-Pass Corn Stover
<b>Densifier</b>	
Densifier type	Pellet mill
Energy (kWh/dry ton)	33.79
Throughput (dry ton/hour/machine)	3.625

Operating conditions (moisture %)	17.0%
Pellet density (lb/ft <sup>3</sup> )	39.42
Pellet durability	98.70%
<b>Cooler</b>	
Moisture removed	1.70%
Energy (kWh/dry ton)	3.02
Throughput (dry ton/hour/machine)	5

a: The effective energy consumption is reduced because only 70% of the material is processed in Stage 2 due to fractional milling. The effective throughput is improved because only 70% of the material is processed in Stage 2 due to fractional milling

## A.5 Transportation and Handling

The 2020 Herbaceous SOT incorporates both bale and pellet transportation. Baled biomass is shipped from field side storage to the depots, while pelleted blendstocks are shipped from depots to the biorefinery. Transportation operations include truck transportation and loading/unloading. Design assumptions for transportation and handling are outlined in Table A-7. Transportation and handling comprises all steps involved in the movement of biomass from multiple local locations to a centralized location (such as a preprocessing facility or biomass depot), including loading, trucking, and unloading. Like the 2019 Herbaceous SOT, the 2020 SOT uses the faster and more efficient Advanced Load Securing System (ALSS) developed in the AGCO-led High-Tonnage Feedstock Logistics project (Webb et al. 2013a), and ensures that each load meets transportation regulations (Figure A-4) using industry data for loading and unloading times. By automating the operation, the ALSS allows the load to be secured without the driver leaving the cab of the tractor (STINGER 2015). The ALSS is reported to load an entire truck in as little as 6 minutes (STINGER 2015). Additional handling operations are required to transfer and queue biomass during preprocessing, and to transfer the blended feedstock to the pretreatment reactor. Surge bins, conveyors, and a truck tipper are used in handling operations.

**Table A-7. Transportation and handling design assumptions in the 2020 Herbaceous SOT.**

Component	Three-pass corn Stover	Two-pass corn Stover
<b>Biomass characteristics during transportation from field to depot</b>		
Format	Bale	Bale
Density	12 lb/ft <sup>3</sup>	12 lb/ft <sup>3</sup>
Moisture content	20%	20%
<b>Biomass characteristics during transportation from depot to biorefinery</b>		
Format	Bulk pellets	Bulk pellets
Density	39.42 lb/ft <sup>3</sup>	39.42 lb/ft <sup>3</sup>
Moisture content	11.53%	11.53%
<b>Truck used during both transportation from field to depot and depot to biorefinery</b>		
Speed	50 miles/hour	50 miles/hour
Type	Day cab	Day cab
<b>Trailer used during transportation from field to depot</b>		
Type	53-ft flatbed with ALSS	53-ft flatbed with ALSS
Volume	3,600 ft <sup>3</sup>	3,600 ft <sup>3</sup>
<b>Trailer used during transportation from depot to biorefinery</b>		
Type	Trailer "Live Floor" 48 feet 2-axle	Trailer "Live Floor" 48 feet 2-axle
Volume	3,600 ft <sup>3</sup>	3,600 ft <sup>3</sup>
<b>Bale Loader</b>		
Capacity	120 tons/hour	120 tons/hour



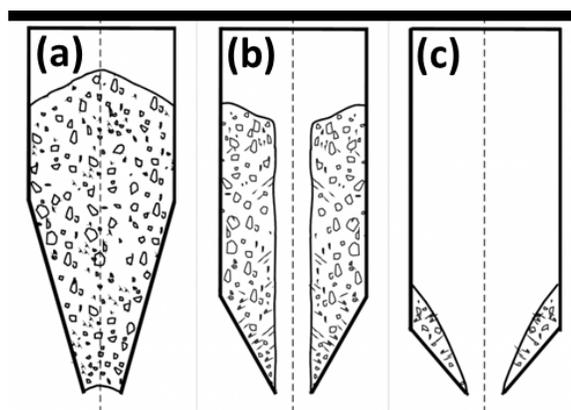
**(a) Manual bale securing system**



**(b) Advanced load securing system**

**Figure A-4. Advanced Load Securing System (ALSS) replacing intense physical requirements to secure a load of bales in 2020 SOT (Source: Stinger)**

Flowability is defined as the relative movement of bulk particles in comparison to neighboring particles and is a measurement of the cohesion and shear stresses in bulk materials. Ground materials (such as bulk corn stover) tend to bridge and clog openings. Flow obstruction, bridging, or arching in addition to inconsistent and unreliable movement of material are common problems in biomass handling and reactor feeding. Figure A-6 shows three common issues experienced in material handling. Arching (bridging) occurs when an arch-shaped obstruction forms above the hopper outlet and stops flow. Ratholing (funneling) occurs when discharge takes place only in a flow channel located above the outlet; once the central flow channel is empty, flow stops. Finally, incomplete clean-out is when not all of the material empties from the sides of the holding container. To address these characteristics, the 2020 Herbaceous SOT incorporates densification to improve feedstock flowability.



**Figure A-5.** Common flow and handling issues encountered when handling biomass. (a) Cohesive arch; (b) Rathole; and (c) Incomplete cleanout. (Source: [www.pharmtech.com](http://www.pharmtech.com))

The 2020 Herbaceous SOT estimates transportation cost based on biomass physical characteristics and equipment used during transportation. Transportation cost has two components, the distance variable cost (DVC) and the distance fixed cost (DFC). The distance variable cost includes the cost of fuel and labor, while the distance fixed cost includes the cost of loading and unloading the truck. Linear regressions were performed to estimate DVC and DFC for each of the biomass bale and blendstock pellet types based on the transportation and handling design assumptions shown above in Table A-8. The regression models were used to estimate the DVC of corn stover and switchgrass bales at \$0.114/dry ton/mile, while the DFC for bale transportation was estimated at \$3.42/dry ton. The DVC for corn stover was estimated to be \$0.083/dry ton/mile with the DFC estimated at \$0.841/dry ton. The values of DVC and DFC were utilized in the expanded least cost optimization model (Roni et al., 2018) to determine the cost-optimum resource usage based on both transportation distance and grower payment. The total transportation costs for bales and pellets (including loading and unloading) are shown as a function of distance from the biorefinery in Table A-8.

**Table A-8.** Total transportation costs for biomass bales and blendstock pellets.

Distance (mi)	Bale Transportation Costs (\$/dry ton)	Pelleted Blendstock Transportation Costs (\$/dry ton)
10	\$4.57	\$1.66
20	\$5.72	\$2.49
30	\$6.83	\$3.33
40	\$8.00	\$4.16
50	\$9.12	\$4.95
60	\$10.24	\$5.79
70	\$11.40	\$6.63
80	\$12.52	\$7.46
90	\$13.69	\$8.26
100	\$14.80	\$9.09
120	\$17.09	\$10.76
140	\$19.37	\$12.39
160	\$21.66	\$14.07
180	\$23.95	\$15.69
200	\$26.23	\$17.38
220	\$28.46	\$19.00
240	\$30.74	\$20.68

Once the optimum resource supply, volume and depot locations were determined, an average weighted transportation distance was calculated for the different types of biomass and the pelleted blendstocks. Table A-9 summarizes the transported biomass, weighted transportation distance and average transportation cost for various biomass and pellet from field to depot and depot to biorefinery in the 2020 Herbaceous SOT. The average weighted transportation distances from field to biorefinery of three-pass corn stover and two-pass corn stover were 100.29 miles and 115.77 miles respectively.

**Table A-9.** Summary of transported biomass, weighted transportation distance and average transportation cost for various biomass and pellet from field to depot and depot to biorefinery in the 2020 Herbaceous SOT case.

Biomass Type	Raw Biomass Purchased (dry tons)	Fields to Depots			Depots to Biorefinery		
		Biomass Transported (dry tons)	Weighted Transportation Distance (miles)	Average Transportation cost (\$/dry ton)	Pellets Transported (dry tons)	Weighted Transportation Distance (miles)	Average Transportation cost (\$/dry ton)
Three-pass corn stover	240,350	219,199	38.01	\$7.66	214,815	62.28	\$5.91
Two-pass corn stover	570,830	520,597	36.43	\$7.48	510,185	79.34	\$7.30
Blended	811,180	739,796	36.90	7.54	725,000	74.28	6.89

### A.6 Depot construction cost for different depot sizes

Construction and infrastructure costs for depots were estimated as follows. For a fixed depot size, the total installed capital investment cost per ton was estimated for the preprocessing, storage and handling operations in the depot. The installed capital cost included all preprocessing, handling and storage equipment; the estimate included instrumentation and control, piping and electrical installation, yard improvement, engineering and supervision, contractor fees, construction and contingency. To estimate the capital layout for construction and infrastructure for individual preprocessing equipment similar to the equipment in this design, an installation factor value of 1.49 was applied, estimated based on Peters et al. (1968). Land cost was calculated assuming 160 acres per distributed depot (including onsite bale storage) at a cost of \$500/acre and was added to the capital cost to determine the loan amount. The required acreage for a 725,000 dry tons/year depot (including onsite bale storage) was estimated at 226 acres. The total cost was amortized over 30 years, assuming a 20% down payment and an 8% interest rate, and divided by the number of delivered tons to give the per ton cost of depot construction and infrastructure, which totaled \$2.30/dry ton for a depot scaled to 725,000 dry tons/year. The above steps were repeated for depot scales ranging from 25,000-700,000 dry tons/year, and the results are shown in Figure A-7.

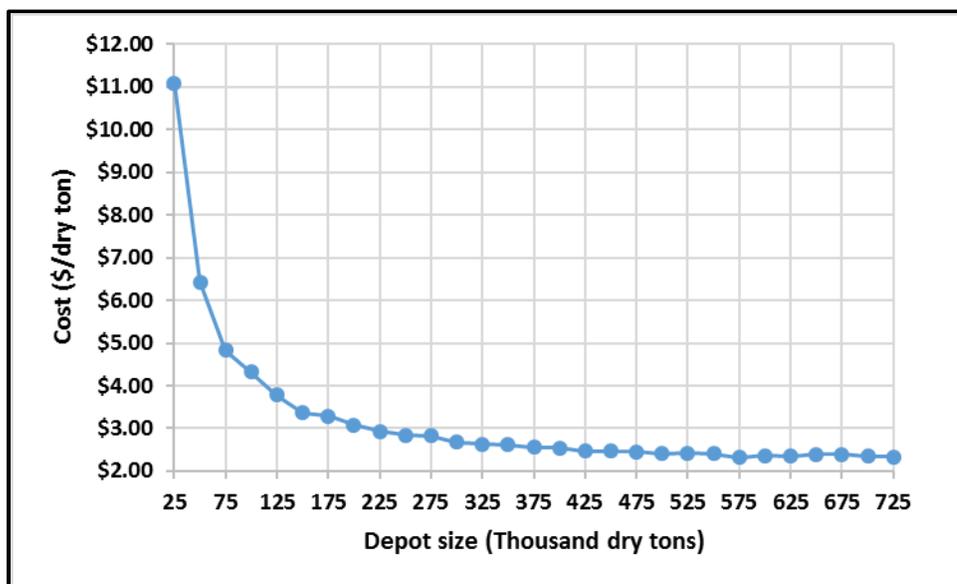


Figure A-7. Estimated depot construction costs as a function of depot scale.

## A.7 Blending

Pellets of each individual blendstock are conveyed into separate storage bins upon receipt from the depots. Pellets are blended in the biorefinery just prior to introduction to the pretreatment reactor feeding system and are blended to the desired ratio during conveyance to the feeder. The three-pass corn stover and two-pass corn stover pellets are blended at a ratio of 29.63%/70.37 respectively, and the blend is conveyed to the throat of the pretreatment reactor.

## A.8 Cost Breakdown by Operation

As described above, an ash dockage equivalent to the biorefinery cost of disposing of ash in excess of the ash specification is applied in the 2020 Herbaceous SOT. Ash disposal costs are assumed to be \$37.63/dry ton of ash (Davis et al. 2013). Delivering the feedstock blend at 10% rather than 20% moisture would incur a cost of to the biorefinery in the form of additional make-up water. This value was calculated from the assumed make-up water cost of \$0.31/ton of water used by Davis et al. (2013). Table A-11 shows the cost breakdown by operation for the individual blendstocks, while Table 12 provides cost information for the three storage types employed.

*Table A-11. 2020 Herbaceous SOT modeled costs for production of blendstock pellets, by operation.*

Cost Element	Three-Pass Corn Stover (\$/dry ton)	Two-Pass Corn Stover (\$/dry ton)
<b>Grower payment</b>	<b>\$21.71</b>	<b>\$20.16</b>
<b>Harvest and collection</b>	<b>\$13.84</b>	<b>\$18.79</b>
Combine	\$0.00	\$0.00
Shredder	\$4.10	-
Baler	\$6.29	\$15.34
Stacker	\$3.45	\$3.45
<b>Storage &amp; queuing</b>	<b>\$6.66</b>	<b>\$6.74</b>
Field side storage	\$4.23	\$4.31
Depot storage	\$0.88	\$0.88
Refinery storage	\$0.12	\$0.12
Handling and queuing at depot	\$1.20	\$1.20
Handling and queuing at refinery	\$0.22	\$0.22
<b>Transportation and handling</b>	<b>\$13.74</b>	<b>\$14.97</b>
Transportation from field to depot	\$7.76	\$7.58
Transportation from depot to refinery	\$5.99	\$7.39
<b>In-plant receiving and preprocessing</b>	<b>\$19.43</b>	<b>\$19.43</b>
Depot construction cost	\$2.52	\$2.52
Bale processor	\$1.80	\$1.80
Hammer mill	\$7.37	\$7.37
Densifier	\$5.61	\$5.61
Cooling	\$0.88	\$0.88
Conveyors	\$0.16	\$0.16
Dust collection	\$0.75	\$0.75
Surge bin	\$0.05	\$0.05
Misc. Equipment <sup>a</sup>	\$0.21	\$0.21
Blending	\$0.07	\$0.07
<b>Dockage</b>	<b>\$2.59</b>	<b>\$0.89</b>
Ash dockage	\$2.56	\$0.86
Moisture dockage	\$0.03	\$0.03
<b>Total delivered blendstock cost</b>	<b>\$77.97</b>	<b>\$80.98</b>

<sup>a</sup> Miscellaneous equipment consists of destringers, moisture meters, bale rejecters, electromagnets, etc.

*Table A-12. 2020 Herbaceous SOT modeled storage cost breakdown for three-pass corn stover and two-pass corn stover.*

Component	Storage TEA parameters 1		Storage TEA parameters 2		Storage TEA parameters 3	
	Three-Pass Corn Stover (\$/dry ton)	Two-Pass Corn Stover (\$/dry ton)	Three-Pass Corn Stover (\$/dry ton)	Two-Pass Corn Stover (\$/dry ton)	Three-Pass Corn Stover (\$/dry ton)	Two-Pass Corn Stover (\$/dry ton)
<b>Storage cost</b>	\$5.54	\$5.49	\$1.84	\$1.85	\$1.84	\$1.85
<b>Dry matter loss cost</b>	\$0.82	\$0.87	\$2.00	\$2.12	\$1.31	\$1.38
<b>Total storage cost</b>	\$6.36	\$6.36	\$3.85	\$3.97	\$3.15	\$3.23

## APPENDIX B – n<sup>th</sup>-Supply Scenario Assumptions and Analysis

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Addressing biomass cost and quality targets is an important BETO Feedstock Technologies (FT) Platform objective. Many of the targets are assumed to be for an n<sup>th</sup>-plant scenario, however, assumptions are based in present time. For example, for resource availability both quantity and types of materials are viewed in terms of what is currently available. Further, the attributes that define the n<sup>th</sup>-Plant scenario are not clear and may be inconsistent across the analysis projects. Additionally, assumptions to quantify harvest cost, grower payment, and farm-gate price, may also differ across projects. Preemptively harmonizing assumptions with other FT projects, in particular, the definition of the n<sup>th</sup>-supply scenario parameters as well as operational parameters such as harvest cost as a function of per-acre yield and profit margin to the grower, will make results across FT projects more comparable and consistent. In this task, analysts at INL and ORNL worked together to define a consistent set of parameters that define the n<sup>th</sup>-supply scenario and supply chain parameters, and annually review operational assumptions to maintain alignment across FT-funded analyses.

Through this work, a set of operational cost assumptions was harmonized and used in feedstock logistic models at INL and ORNL such as the Least-Cost Formulation, POLYSYS, and the Supply Characterization Models. A two-step process was used to reduce the problem size using a modified version of INL's Least-Cost Formulation model, a Mixed Integer Linear Programming (MILP) Model, to model the delivery of on-spec biomass of multiple crops that considers biomass quantity and quality at a specified total delivered feedstock cost. The first step was to determine a set of candidate locations for biorefineries and depots nationwide. In the second step, biorefineries and depots of different capacity sizes were located using different scenarios.

Using the acids pathway fuel yield of 44.8 GGE/dry ton presented by Davis et al. (2018), our case study for 2022, which located a total of 59 biorefineries (42.8M dry tons), translates to 1.9 billion GGE. Only 0.12% of the RFS2 targets to produce 16 billion gallons of cellulosic biofuels by 2022 could be achieved with corn stover and switchgrass. Additionally, based on this analysis, only 29.68M dry tons of switchgrass and corn stover could be delivered at \$71.26 per dry ton (2016\$) delivered to the pretreatment reactor throat by 2030. These translates into 41

biorefineries, or 1.3 billion GGE. Hence, the decrease in targeted cost per dry ton delivered from \$79.07 in 2022 to \$71.26 in 2030, decreases the feasible production of biofuels by 0.6 billion GGE.

## B.1 Harmonized herbaceous operational assumptions

Logistics costs in different formats were harmonized based on the required input parameters for the different feedstock logistic models at INL and ORNL such as the Least-Cost Formulation, POLYSYS, and the Supply Characterization Models. Note that biomass sorghum was not one of the feedstocks considered in Roni et al. (2018). Table B.1 and Table B.2 present inputs used for analysis at ONRL based on joint-efforts to harmonize operational costs. Table B.3 and Table B.4 present inputs used for analysis at INL based on joint-efforts to harmonize operational costs.

**Table B.2** Comparison of costs used in a conventional supply chain in the BT16 (USDOE 2016), the 2018 Herbaceous State of Technology Report (SOT) (Roni et al. 2018) costs translated for a conventional supply chain, and harmonized costs assumptions for a conventional supply chain in a format to be used by the models at ORNL.

Farmgate to biorefinery operation	Costs, \$ Mg <sup>-1</sup> (\$ ton <sup>-1</sup> )		
	BT16 <sup>1</sup>	2018 SOT <sup>2</sup>	Harmonized
<b>Corn stover</b>			
Storage on-farm	4.32 (3.92)	4.38 (3.97)	4.38 (3.97)
Field side handling and queuing	3.57 (3.24)	3.77 (3.42)	3.77 (3.42)
Storage at biorefinery	1.73 (1.57)	0.97 (0.88)	0.97 (0.88)
Grinding	15.43 (14)	13.15 (11.93)	13.15 (11.93)
Handling at biorefinery	-	2.93 (2.66)	2.93 (2.66)
Dockage for moisture	3.7 (3.36)	0.03 (0.03)	3.7 (3.36)
Dockage for ash	2.99 (2.71)	2.99 (2.71)	2.99 (2.71)
<b>Total</b>	<b>31.75 (28.8)</b>	<b>27.98 (25.38)</b>	<b>31.65 (28.71)</b>
<b>Switchgrass and Miscanthus</b>			
Storage on-farm	4.32 (3.92)	3.33 (3.02)	3.33 (3.02)
Field side handling and queuing	3.57 (3.24)	1.48 (1.34)	3.77 (3.42)
Storage at biorefinery	1.73 (1.57)	0.97 (0.88)	0.97 (0.88)
Grinding	15.43 (14)	10.38 (9.42)	10.38 (9.42)
Handling at biorefinery	-	2.98 (2.70)	2.98 (2.70)
Dockage for moisture	3.7 (3.36)	0.03 (0.03)	3.7 (3.36)
Dockage for ash	2.57 (2.33)	0.58 (0.53)	2.57 (2.33)
<b>Total</b>	<b>31.33 (28.42)</b>	<b>19.75 (17.92)</b>	<b>27.7 (25.13)</b>

<sup>1</sup>\$2014, <sup>2</sup>\$2016

**Table B.3** (Continued)

Farmgate to biorefinery operation	Costs, \$ Mg <sup>-1</sup> (\$ ton <sup>-1</sup> )
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	BT16 <sup>1</sup>	2018 SOT <sup>2</sup>	Harmonized
<b>Biomass sorghum</b>			
Module building	9.14 (8.29)	-	9.14 (8.29)
Storage	4.32 (3.92)	-	4.32 (3.92)
Load truck	7.9 (7.17)	-	7.9 (7.17)
Storage at biorefinery	1.73 (1.57)	-	1.73 (1.57)
Grinding	9.14 (8.29)	-	9.14 (8.29)
Dockage for moisture	7.41 (6.72)	-	7.41 (6.72)
Dockage for ash	2.99 (2.71)	-	2.99 (2.71)
<b>Total</b>	<b>42.63 (38.67)</b>	<b>-</b>	<b>42.63 (38.67)</b>

<sup>1</sup>\$2014, <sup>2</sup>\$2016

**Table B.4** Harmonized costs assumptions for an advanced supply chain in a format to be used by the models at ORNL.

Farmgate to depot to biorefinery operation	Costs, \$ Mg <sup>-1</sup> (\$ ton <sup>-1</sup> )	
	Corn stover	Switchgrass and Miscanthus
<b>Storage and queuing</b>	<b>7.05 (6.4)</b>	<b>6.49 (5.89)</b>
Field	4.38 (3.97)	3.33 (3.02)
Depot	2.3 (2.09)	2.45 (2.22)
Biorefinery	0.37 (0.34)	0.72 (0.65)
<b>In-plant receiving and processing</b>	<b>24.97 (22.65)</b>	<b>24.31 (22.05)</b>
Field	0 (0)	0 (0)
Depot	24.97 (22.65)	24.31 (22.05)
Biorefinery	0 (0)	0 (0)
<b>Dockage for ash and moisture</b>	<b>3.02 (2.74)</b>	<b>0.62 (0.56)</b>
Field	0 (0)	0 (0)
Depot	0 (0)	0 (0)
Biorefinery	3.02 (2.74)	0.62 (0.56)
<b>Fixed cost load and unload from farm to depot</b>	<b>3.77 (3.42)</b>	<b>3.77 (3.42)</b>
<b>Fixed cost load and unload from depot to biorefinery</b>	<b>0.91 (0.83)</b>	<b>0.87 (0.79)</b>
<b>Cost per hour from farmgate</b>	<b>4.43 (4.02)</b>	<b>4.43 (4.02)</b>
<b>Cost per mile from farmgate</b>	<b>0.04 (0.03)</b>	<b>0.04 (0.03)</b>
<b>Cost per hour from depot</b>	<b>3.22 (2.92)</b>	<b>3.18 (2.89)</b>
<b>Cost per mile from depot</b>	<b>0.03 (0.02)</b>	<b>0.03 (0.02)</b>

**Table B.5** Harmonized cost assumptions for the conventional supply chain in a format to be used by the Least-Cost Formulation model at INL. CS3P = Three-pass corn stover, CS2P = Two-pass corn stover and SW = Switchgrass.

	Feedstock
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Cost Description	Feedstock	Location	CS3P	CS2P	SW
Farmgate Price	Bale	Field	\$30-90 <sup>1</sup>		\$40-90 <sup>1</sup>
Storage	Bale	Field	\$3.97	\$4.10	\$3.02
Storage, Handling and Queuing	Bale	Biorefinery	\$3.54		\$4.01
Processing Cost	Bale to fuel	Biorefinery	\$11.93		\$9.42
Ash Dockage	Bale	Biorefinery	\$6.19	\$2.24	\$5.69
Moisture Dockage	Bale	Biorefinery	\$0.00	\$0.00	\$0.00
Transportation Fixed Cost or Fieldside Handling and Queuing	Bale	Field to Biorefinery	\$3.42		
Transportation Variable Cost	Bale	Field to Biorefinery	\$0.114 <sup>2</sup>		

<sup>1</sup>2014\$, <sup>2</sup>\$ /mile/dry ton

**Table B.6** Harmonized cost assumptions for the advanced supply chain in a format to be used by the Least-Cost Formulation model and the study presented in this report. CS3P = Three-pass corn stover, CS2P = Two-pass corn stover and SW = Switchgrass.

Cost Description	Feedstock Format	Location	Feedstock		
			CS3P	CS2P	SW
Farmgate Price	Bale	Field	\$30-90 <sup>1</sup>		\$40-90 <sup>1</sup>
Storage	Bale	Field	\$3.97	\$4.10	\$3.02
Storage, Handling and Queuing	Bale to pellets	Depot	\$2.09		\$2.22
Storage, Handling and Queuing	Pellets	Biorefinery	\$0.34		\$0.65
Processing Cost	Bale to pellets	Depot	\$19.47		\$18.77
Ash Dockage	Pellets	Biorefinery	\$2.71	\$0.98	\$0.53
Moisture Dockage	Pellets	Biorefinery	\$0.03	\$0.03	\$0.03
Transportation Fixed Cost or Field- side Handling and Queuing	Bale	Field to Depot	\$3.42		
Transportation Variable Cost	Bale	Field to Depot	\$0.114 <sup>2</sup>		
Transportation Fixed Cost	Pellets	Depot to Biorefinery	\$0.829		\$0.792
Transportation Variable Cost	Pellets	Depot to Biorefinery	\$0.082 <sup>2</sup>		\$0.081 <sup>2</sup>

<sup>1</sup>2014\$, <sup>2</sup>\$ /mile/dry ton

## B.2 Feedstock location and availability

The base-case scenario county-level feedstock values reported in the BT16 for corn stover and switchgrass (estimated to grow on cropland and pastureland) were analyzed including year 2022, 2030, and 2040 (Langholtz et al., 2016) (Figure B.1).

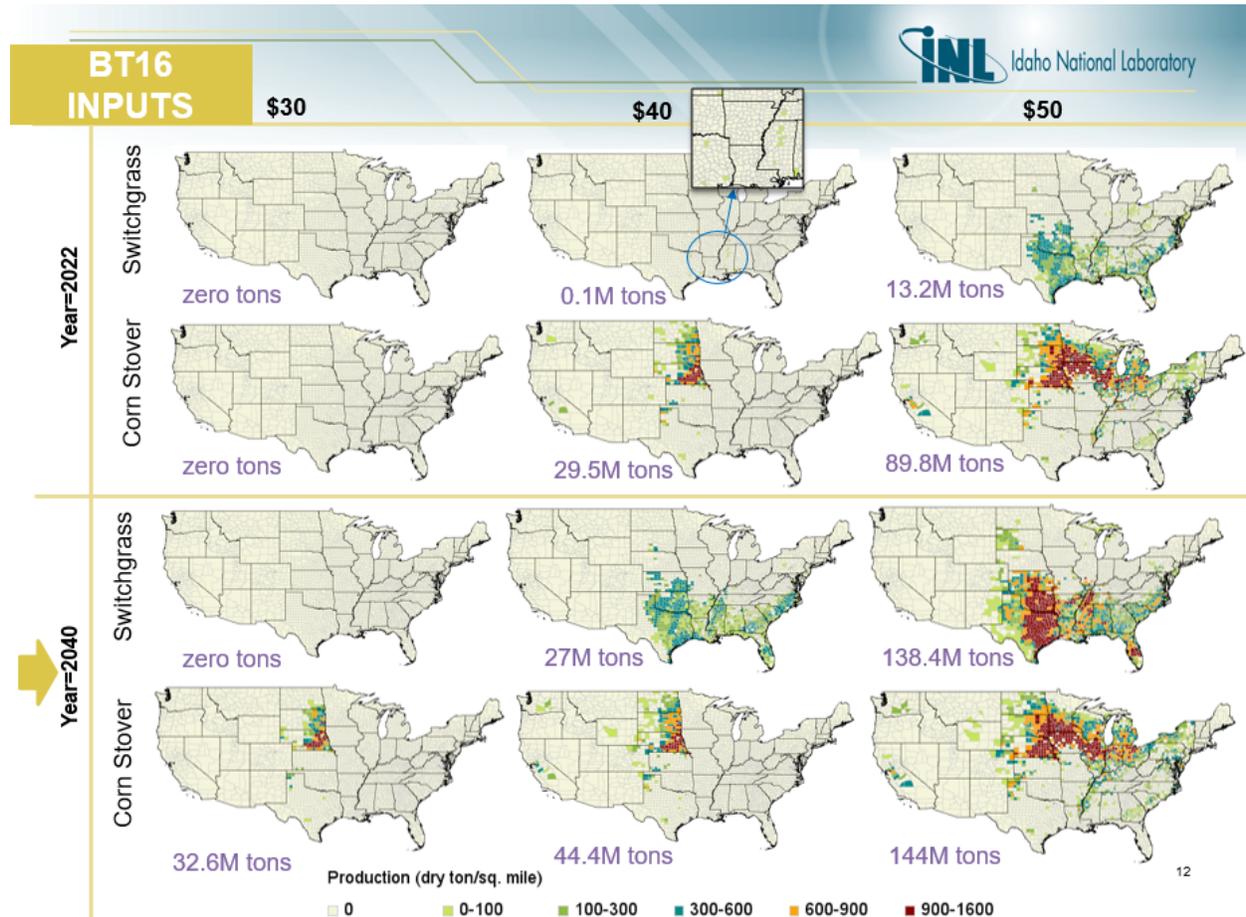


Figure B.1 BT16 biomass availability per county.

### B.3 Reducing the problem size and creating a demand run for POLYSYS

Given the computational size of the problem scope, we used a two-step process to reduce the problem size using a modified version of INL’s Least-Cost Formulation model, a Mixed Integer Linear Programming (MILP) Model to deliver on-spec biomass of multiple crops that considers biomass quantity and quality at a specified total delivered feedstock cost. The first step was to determine a set of candidate locations for biorefineries and depots nationwide. In the second step, biorefineries and depots of different capacity sizes were located using different scenarios. In that analysis, 263 depots were supplied with 70,711,935 dry tons of corn stover from 416 sources and 32,316,373 dry tons of switchgrass from 751 sources (Figure B.2).

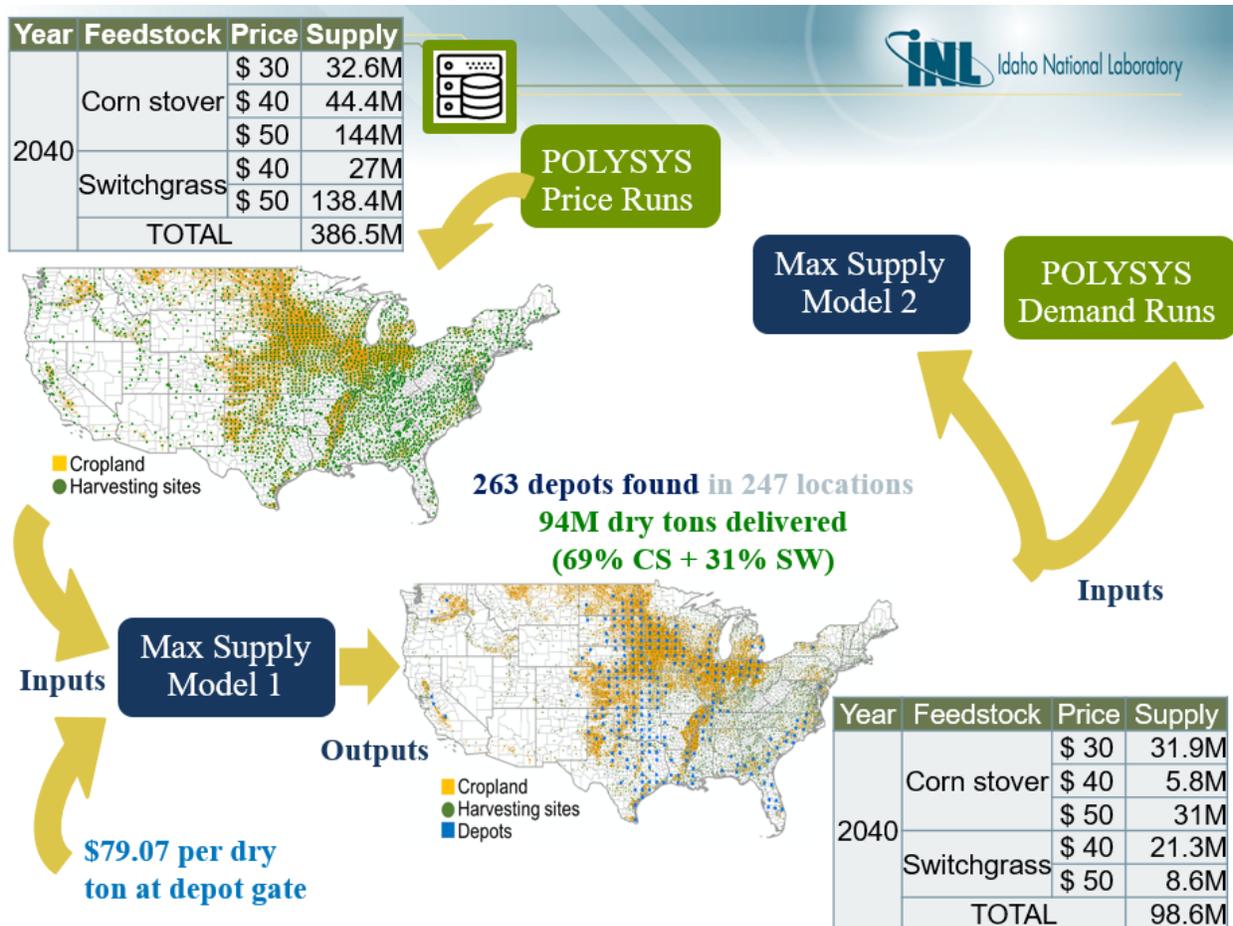


Figure B2. Reducing the problem size and creating a demand run for POLYSYS.

## B.4 POLYSYS demand run

In efforts to further harmonize our model with POLYSYS demand and supply runs (in green), we used the MILP outputs (263 potential depot locations) as inputs to demand runs for POLYSYS. Note that with the demand runs, in total, more biomass becomes available. While switchgrass estimations are higher at both farmgate prices, corn stover increases are only seen in the \$40 and \$50 price levels (Figure B.3). The outputs from the POLYSYS demand runs were also inputs to the MILP presented in this study to find biorefineries and depots and the results are presented in Table B.5

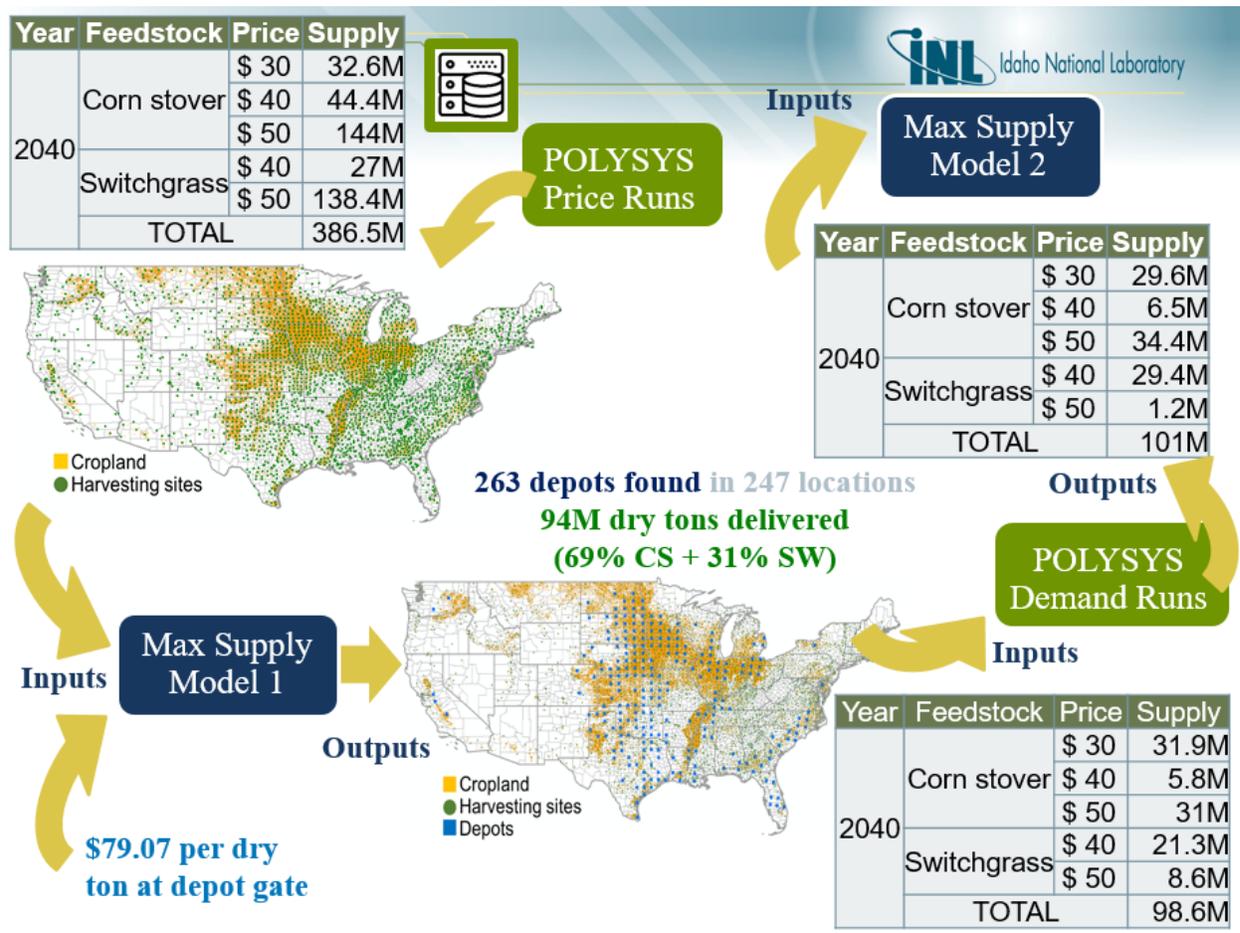


Figure B.3 POLYSYS demand runs

Table B.5 Locating Biorefineries and Depots from the POLYSYS demand runs

Scenario		\$30 (dt)	\$40 (dt)	\$50 (dt)	Total (dt)	Number of Facilities
\$79.07 /dry ton	SW	-	31M	1M	32M (36%)	210 Depots, 125 Biorefineries
	CS2P	2M	12M	12M	26M (29%)	
	CS3P	22M	2M	8M	32M (35%)	
Total feedstock collected					90.6M	

## B.4 n<sup>th</sup>-Supply Scenario References

Davis, R. E., Grundl, N. J., Tao, L., Bidy, M. J., Tan, E. C., Beckham, G. T., ... & Roni, M. S. (2018). *Process Design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels and coproducts: 2018 biochemical design case update; biochemical deconstruction and conversion of biomass to fuels and products via integrated biorefinery pathways* (NREL/TP-5100-71949). National Renewable Energy Lab. (NREL), Golden, CO (United States).

Langholtz, M. H., Stokes, B. J., & Eaton, L. M. (2016). 2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstock. *Oak Ridge National Laboratory, Oak Ridge, Tennessee, managed by UT-Battelle, LLC for the US Department of Energy, 2016*, 1-411.

Roni, M. S., Hartley, D. S., Griffel, M., Hu, H., Nguyen, Q. A., Cai, H., & Thompson, D. N. (2020). *Herbaceous feedstock 2018 state of technology report* (INL/EXT-18-51654-Rev000). Idaho National Laboratory (INL), Idaho Falls, ID (United States).